Impacts of Climate Policy on Urban Air Pollution: Implications for Policy Design for Integrating Air-quality Co-benefits

by

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Submitted to the Engineering Systems Division
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Abstract

Recent scientific assessments reveal interactions between global climate change and urban air pollution and imply that opportunities exist to simultaneously deal with these two issues from a policy perspective. This thesis addresses one side of the topic: the air-quality co-benefits of a climate policy, focusing on the regional, temporal, and specie-specific responses. From a policy perspective, it is crucial to understand these responses in order to set a sound framework for climate policy with co-benefits.

This thesis research establishes the links between a newly developed detailed model of urban-scale chemical and physical processing (Metamodel) and the Massachusetts Institute of Technology (MIT) Integrated Global Systems Model (IGSM). These linkages will ultimately enable the sub-components of the IGSM, including the new Metamodel, to communicate interactively. As a first step, the study conducts a preliminary analysis by running the Metamodel in offline mode by providing the actual dataset from the IGSM to the Metamodel exogenously. The study uses two scenarios: the "CO_2 stabilization policy" (450ppm policy) and the "no policy" cases and compares the impacts of the 450ppm policy for the period from 2001 through 2100 on the key air pollutants: O_3, CO, NO_2, SO_2, HCHO, sulfate aerosols, black carbon, organic carbon, and nitrate aerosols.

The findings of the study are 1) the 450ppm policy will likely reduce key air pollutants except O_3; 2) the variability of the impacts by species is significant – the magnitude of the reductions would be largest for SO_2, more than -10%, followed by organic carbon, nitrate aerosols, HCHO, sulfate aerosols, and black carbon, between -10% to -5%, though CO and NO_2 would be much less affected, less than -5%; 3) for the affected species except SO_2 and sulfate aerosols, the impacts become larger as time advances; 4) the magnitude of the impacts vary widely by region due to not only the reduction of emissions but also meteorological conditions; and 5) the variability of the results for sulfate aerosols, BC, OC, and nitrate aerosols may be highly uncertain compared to other species, taking into account the large statistical uncertainties of the monthly mean concentrations.

The thesis also explains other methodological challenges for assessing the air-quality co-benefits. Furthermore, the thesis examines barriers to implementation of the air-quality co-benefits in practice and, finally, provides implications for future policy design based on the above findings.

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Chapter 1. Introduction

1.1. Research Motivation

Many scientists and policy makers have recently discussed the co-benefits of addressing global climate change and urban air pollution. Scientists have investigated urban air pollution since the 19th century. It causes relatively local and regional health risks, imposes damages on cultural heritage, agriculture, and other assets. Therefore, most developed countries have established air pollution control policies, though there is little linkage or consistency with policies in other countries and there is little need to do so. The issue of climate change has risen to greater prominence recently and climate scientists have believed the possible impacts of climate change would be global and happen in the long term. Therefore, appropriate actions will be required in worldwide cooperation.

In both contexts, the recent scientific assessments (Houghton et al., 2001; EEA, 2003; Swart et al., 2004; Prinn, 2005) have revealed the interactions between the two problems. They imply that there would be opportunities to simultaneously deal with the two issues that have been separately discussed before. In fact, the International Panel on Climate Change (IPCC) has stated, in its second, third, and fourth assessment reports, that capturing synergies and

avoiding trade-offs when addressing the issues of climate change and urban air pollution simultaneously through a single set of technologies or policy measures potentially offers large cost reduction and additional benefits[1] (B. Metz O. D., 2007)

The international community has started responding to the assessments; organizations such as the World Bank, the Asian Development Bank, the United Nations Environment Programme (UNEP), and the United Nations Environment and Social Commission for Asia and the Pacific (UNESCAP) have started to investigate how to integrate co-benefits in practice[2]. Some ANNEX I[3] countries such as the United States and Japan are individually developing integrated approaches, primarily through bilateral cooperation, to help developing countries tackle economic development and its resulting negative effects such as air pollution and climate change; China, India, Indonesia, Chile, and other rapidly growing countries have became active in taking advantage of their efforts and collaborations to clean the environment as well as addressing climate change. Even the private sector has started to explore opportunities to take advantage of the side effects of their efforts to mitigate CO_2 emissions.

Given this increasing awareness, the ultimate goal of this thesis is to provide implications for

[1] Additional benefits are usually called secondary benefits, co-benefits, or ancillary benefits, though the last phrase will be used throughout this thesis.

[2] More information is available on http://www.iges.or.jp/jp/cp/activity20100311cb.html

[3] http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php

future policy design and implementation of co-benefits of climate policies and urban air pollution controls. It aims to complement the current discussions over co-benefits and to help policy makers have a concrete foundation based upon scholarly viewpoints.

1.2. Thesis Organization

The thesis is organized in the following manner. The next chapter frames the thesis questions and covers the relevant issues. Moreover, since the concept, "co-benefits," and the interactions between climate change and urban air pollution have various aspectsI, the scope of this study is also addressed.

The third chapter describes the methodology the study used. This study is the first attempt to link the newly developed model of urban air chemical and physical processing (Metamodel) to the MIT Integrated Global System Model (IGSM). Although the Metamodel and the IGSM should ultimately interact with each other, this study utilizes the Metamodel in stand-alone mode, and as such is exogenously forced by atmospheric conditions and emissions provided by the IGSM outputs. This framework is widely used in coupled-model development and, as such, serves as an important test to isolate its behavior and response to (simulated) climate and human forcings within the IGSM.

Chapter Four centers the provisionally global-scale quantitative assessments of future impacts of a climate policy on urban air pollution (reduction). Since the model enables the analysis at the 1-by-1-degree scale, the study first compares regional differences in the impacts. Furthermore, since the model includes highly various air pollutants including aerosols, the comparisons between species are presented as well as different periods of time.

Chapter Five describes methodological challenges for assessing air-quality co-benefits and effects of integrating them on typical policy measures to understand the basics of policy designs for air-quality co-benefits. In addition, the chapter examines current barriers and preliminary implications of implementing air-quality co-benefits in policy design so that they can be taken into account in the near future in a better and more appropriate manner.

Finally, Chapter Six concludes the thesis with limitations and suggestions for future work.

Chapter 2. Framing Issues

2.1. Framing Urban Air Pollution Issue

2.1.1. Key Social Factors Causing Urban Air Pollution – Urbanization, Industrialization, and Motorization

Urban air pollution closely relates to urbanization, industrialization, and motorization. Urbanization is the increase in the urban proportion of the total population[4] through the movement of people from rural to urban areas. It increases the total number of people and, in many cases, the density of an urban area, which results in changes in the urban environment, the standard of living, and culture. In 2008, more than half of the world's population lived in urban areas for the first time (UNFPA, 2007) and the urban population had grown to about 3.5 billion in 2010 and will reach about 5 billion in 2030 (WUP, 2009). The changes in the proportions of urban population by region indicate that the urban populations in Asia and Africa will almost double between 2000 and 2050. This means that Asia and Africa will have approximately 36% - 60% of its population living in urban areas, and that the other regions, Europe, Northern America, and Latin America including Caribbean will have more than 80 percent of their populations in urban areas by 2050 (Figure 1). The regional shares of the total urban population also imply that while Africa accounts for 11% of the world's urban

[4] The definition of urbanization may vary. This paper follows the definition by the United Nations or its related organizations.

population in 2000, the proportion will nearly double to 20% by 2050 (Figure 2). Specifically, although India, China, Indonesia, Thailand, Vietnam, Pakistan, and Bangladesh are currently less urbanized, their annual growth rates of urbanization are higher than the currently highly urbanized countries having the large population sizes such as United States, Germany, and Japan, and that these less urbanized countries have far larger population sizes (United Nations, 2005). These estimates imply that urban air pollution, which partly results from urbanization and used to be a problem in more urbanized countries, would become more serious in the currently less-developed, large populated countries.

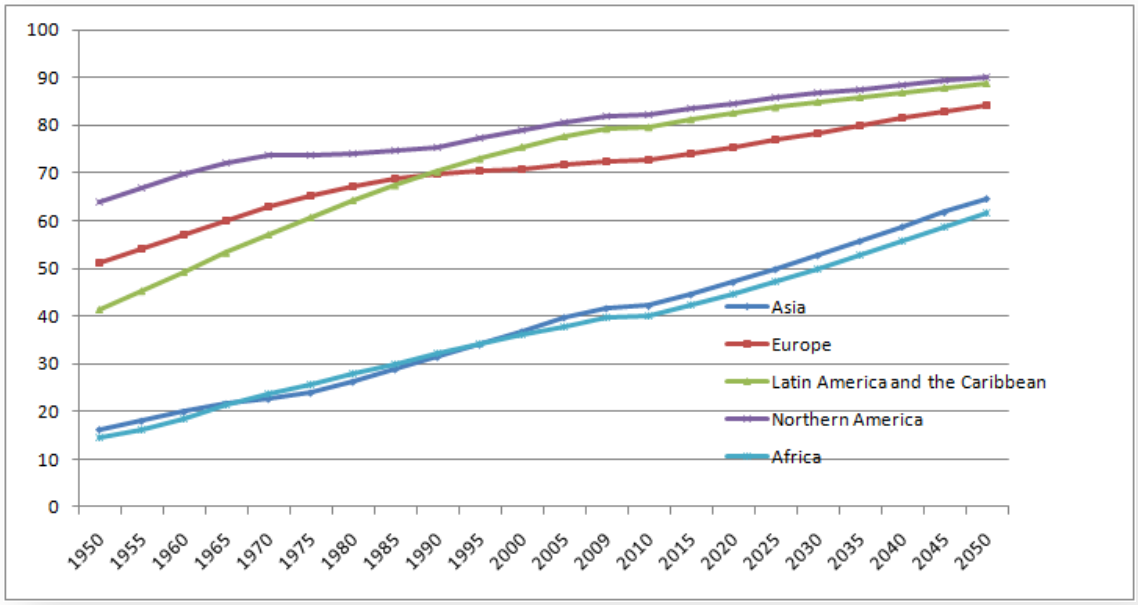

Figure 1. The Percentages of Urban Population by Regions
(Source: World Bank)

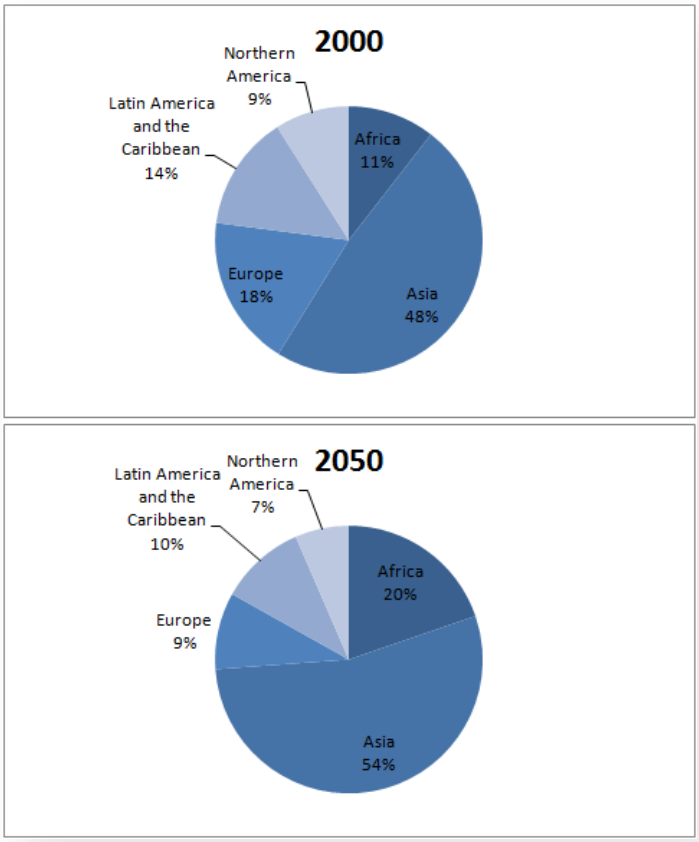

Figure 2. The Regional Shares of the World's Urban Population in 2000 and 2050(prediction).
(Source: World Bank)

Urban air pollution also relates to industrialization, which is a process of socio-economic change, primarily through technological improvements and innovations. The more a country industrializes, the more efficient technologies are utilized. For instance, while people in developed countries commonly use electricity for lighting, there are still non-electrified areas in some parts of Africa and Asia where people normally use oil lamps for lighting, cooking, and heating. Simultaneously, industrialization enhances the country's energy consumption due to increases in industrial activities, i.e. expanding manufacturing production and

consumption, which results in an increase in the emissions of CO_2 and air pollutants. Figure 3 demonstrates that the more developed regions such as North America and Europe account for more than twice the CO_2 emissions per capita. Industrialization also accompanies motorization. Although motor vehicles enable people to work more efficiently and conveniently, they cause congestion in traffic and local air pollution.

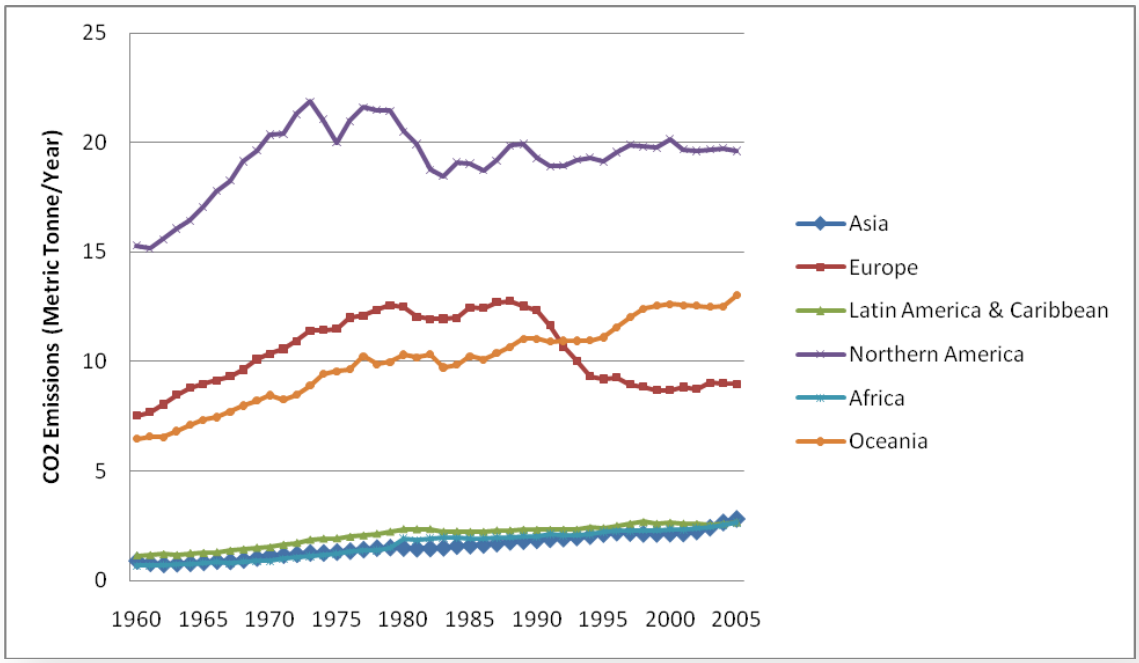

Figure 3. The Emissions of CO_2 per Capita by Regions (Source: World Resource Institute.)

2.1.2. Emission Sources of Air Pollutants

The main cause of urban air pollution is the emissions from the combustion of fossil fuels (coal, oil, and natural gas) in the transportation, electricity generation, industrial processes, and domestic sectors. The key pollutants, for instance, are CO and NO_x from the

transportation sector, whereas VOC, SO_2, and particle matters (PM), such as PM2.5 and PM10, are emitted mainly from the electricity generation and industry sectors.

Overall, the sectoral shares in the emissions of each of the major air pollutants are shown in Figure 4. While the ratios of emission sources for each pollutant, the types of pollutants, and the levels of the impacts vary by city due to a different manner and pace of urbanization, industrialization and motorization of a city, Figure 4 demonstrates that electricity generation, fossil fuel combustion, industrial processes, non road equipment, on road vehicles, road dust, solvent use, and waste disposal particularly are attributed to urban air pollution. The on-road vehicle sector accounts for more than half of the emissions of CO and about 25% of its emissions are attributed to the non-road equipment sector. The on-road vehicle sector also accounts for approximately 35% of the emissions of NOx, and about 20% of its emissions are attributed to electricity generation. More than half of larger Particulate Matters (PM10) come from roads as dusts, which also produce about 20% of the emissions of smaller Particulate Matters (PM2.5). Furthermore, more than 70% of the emissions of SO_2 are caused by electricity generation and solvent use and on-road vehicles account for 30% of the emissions of VOC respectively.

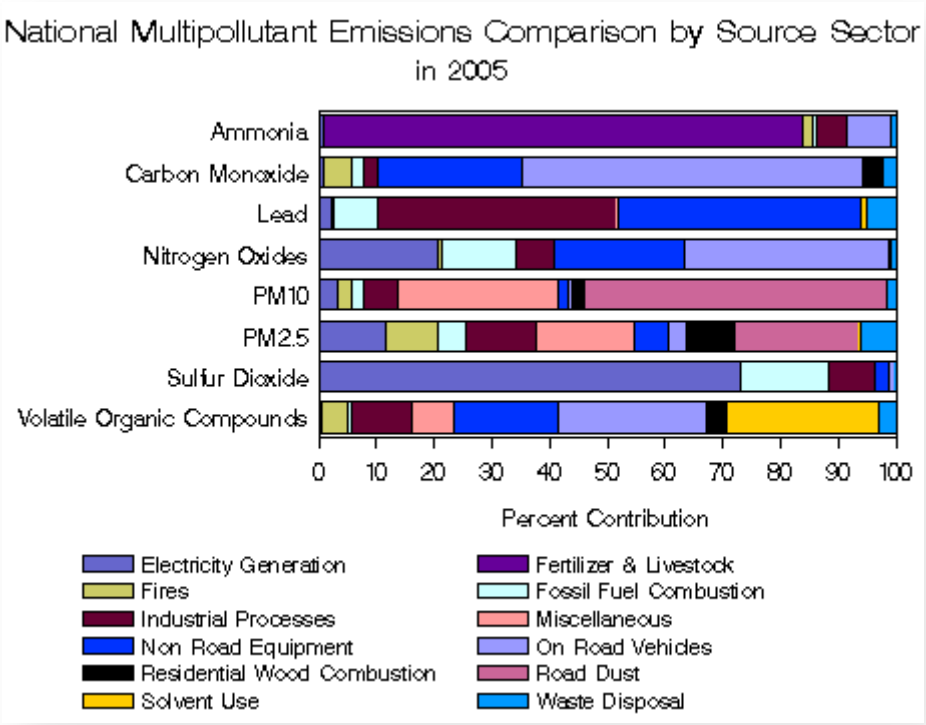

Figure 4. National Multi pollutant Emissions Comparison by Source Sector in 2005) (Source: US-EPA based on the WHO Air Quality Guideline)

2.1.3. Key Urban Chemical and Physical Processes

A. Initiation Processes

The chemical and physical reaction processes in the troposphere are much more complicated than in the stratosphere. However, the processes normally start with the production of the hydroxyl (OH) radical through the photolysis of the sun's ultraviolet light. Since the OH radical is unreactive toward O_2 and O_3, the most abundant oxidants in the atmosphere, it reacts with atmospheric trace gases (John H. Seinfeld, 2006). While they are generally unreactive, they produce the OH radical through the following reaction, triggered by O_3 photolysis:

$O_3 + hv(<319nm) \rightarrow O_2 + O$ (reaction 1a)

$\rightarrow O_2 + O(^1D)$ (reaction 1b)

The ground-state oxygen atom, then, reacts with O_2 to reform O_3.

$O + O_2 + M \rightarrow O_3 + M$ (reaction 2)

Most of the excited singlet oxygen, $O(^1D)$, then, are stabilized to the ground-state oxygen atom, O, by colliding with the abundant molecules, N_2 or O_2 by the following reaction.

$O(^1D) + M \rightarrow O + M$ (reaction 3)

However, O(1D) collides with the H_2O molecule, producing two OH radicals, though the following reaction rarely occurs as the bond energy of OH in H_2O is quite strong:

$O(1D) + H_2O \rightarrow 2OH$ (reaction 4)

The above reaction mechanism sustains its concentration on the order of 10^6 molecule cm^{-3} during daylight hours, and the OH radical is consumed by the reactions to other trace gases including air pollutants due to its high reactivity. Since its concentration varies by the amount

of sunlight and by location, the subsequent reactions would also differ by area, which would result in the special difference in urban air processing.

B. Formation of Tropospheric Ozone – One of the Important Air Pollutants

Wang indicates that urban air pollution not only directly changes the O_3 concentrations (Wang, 1986), but Levy (1972) shows it also indirectly alters them through changes in the OH radical concentration. The current understanding of the formation of tropospheric ozone is as follows. O_3 is produced through the reactions of the OH radical to urban air pollutants: the reaction of OH to organic carbon compounds such as CO and VOC, which produce hydroxyl peroxy radicals (HO_2, RO_2); and the reaction of RO_2 to NO_x, producing O_3. Although other reaction paths affect the cycle of forming O_3, carbon-containing compounds and NO_x are involved as the key species to produce O_3.

In the presence of NOx and RO_2, O_3 is formed by the following chain:

$NO + RO_2 \rightarrow NO_2$ (reaction 5)

$NO_2 + hv \rightarrow NO + O(^3P)$ (reaction 6)

$O(^3P) + O_2 + M \rightarrow O_3 + M$ (reaction 7)

The first reaction occurs because RO_2 is a reactive oxidant, and the second reaction, the photolysis of NO_x occurs when NO_x comes across the sunlight less than 424nm, producing NO and the O radical. The O radical eventually forms O_3, which is the only path to produce O_3 in the troposphere.

Although the third reaction is the only one to produce O_3 in the troposphere, the following reaction removes NO_x and RO_2, forming nitric acid:

$OH + NO_2 + M \rightarrow HNO_3 + M$ (reaction 8)

Furthermore, the formed O_3 can be consumed by reacting to NO and forming NO_2 again:

$NO + O_3 \rightarrow NO_2 + O_2$ (reaction 9)

As stated, peroxy radicals, RO_2, are produced by the reaction of OH to carbon-containing compounds. One example is the reaction of OH to CO.

$CO + OH \rightarrow CO_2 + H$ (reaction 10)

$H + O_2 + M \rightarrow HO_2 + M$ (reaction 11)

Another source of RO_2 is CH_4, which is a GHG. CH_4 also reacts with OH, which implies that CH_4 can contribute to global warming in the two different paths. Larger carbon-containing compounds also react to OH in a similar manner producing RO_2.

$CH_4 + OH \rightarrow H_2O + CH_3$ (reaction 12)

$CH_3 + O_2 + M \rightarrow CH_3O_2 + M$ (reaction 13)

In the process to forming ozone, some complexities exist. First, ozone production efficiency decreases as the concentration of NOx increases (John H. Seinfeld, 2006). Second, the ratio of VOC relative to NOx determines the productivity of O_3, which can be explained by "the Ozone Isopleth Plot" (John H. Seinfeld, 2006). The plot indicates the independence of the O_3 production on the initial concentrations of both NO_x and VOC, though it depends on the ratio of VOC to NO_x thereafter. Although the series of reactions described above represent key chains to increase or decrease the O_3 production, the rate of the O_3 production is also affected by other climatic and topological conditions and the existence of other trace gases.

2.1.4. Impacts and Damages of Urban Air Pollution

In the short term, urban air pollution causes impacts on society that differ from those of global climate change. The most notable consequence is the impact on public health due to

the exposure to harmful pollutants. The immediate responses result in respiratory diseases, whereas the delayed ones are cancers and a decrease in life expectancy. Figure 5 below shows that the number of deaths attributable to urban air pollution is larger in developed countries and in China, Brazil, and Eastern Europe, which are currently growing rapidly. The other impacts of urban air pollution range from material damages on cultural heritages, urban ecosystems, agricultural crops, all of which eventually impose economic costs on society.

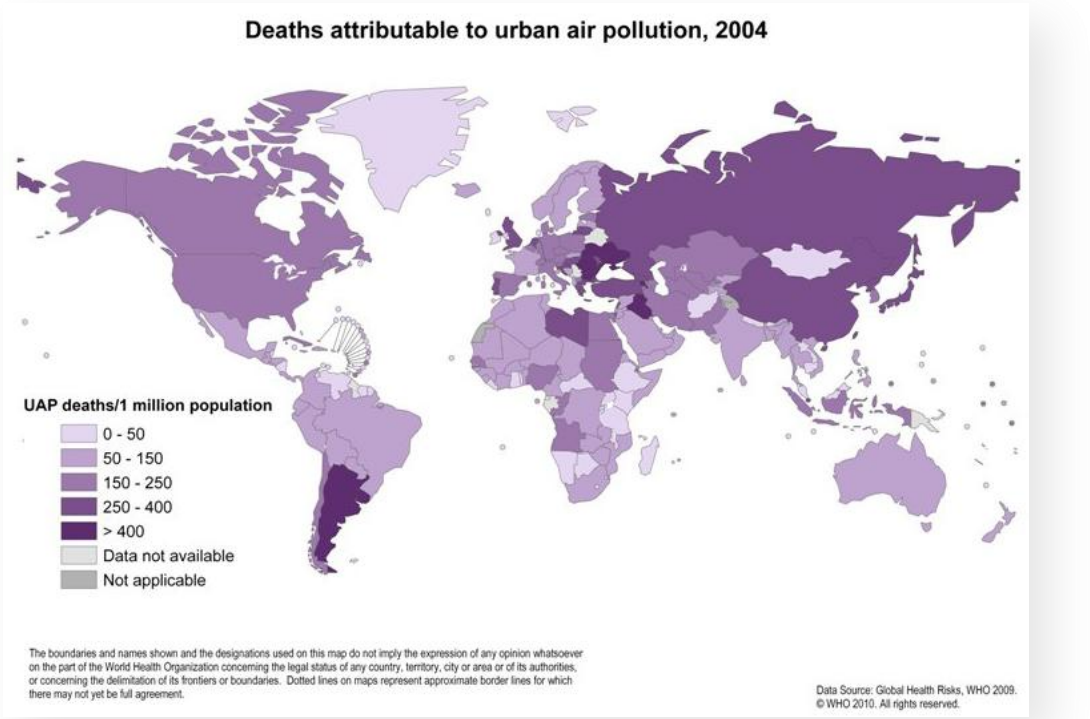

Figure 5. The Number of Deaths Attributable to Urban Air Pollution (2004)
(Source: the World Health Organization)

2.1.5. Urban Air Pollution in the Context of Global Climate Change

As shown in Figure 6, some of the key atmospheric species have a residence time and a spatial scale of variability different from those of longer-lived GHGs such as CH_4, CH_3Br, and CH_3CCl_3. This means that most air pollutants are settled chemically or physically before being transported globally. Therefore, urban air pollution is believed to have more impacts at the local or regional scale rather than at the global scale.

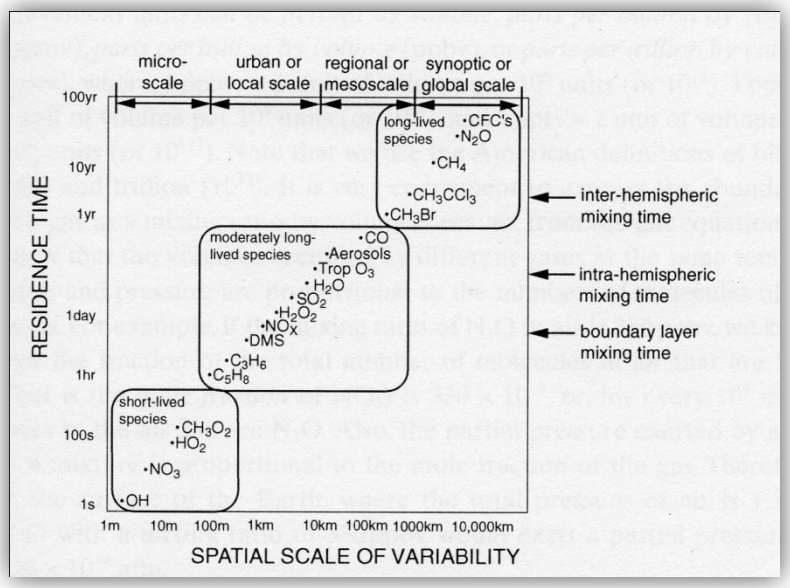

Figure 6. Spatial and temporal scales of variability for some atmospheric constituents
(Note: The temporal scale is represented by residence time.)
(Source: (Hubbs, 2000))

However, some air pollutants and species produced through secondary reactions have either positive or negative effects on the atmospheric radiative flux balance and the Earth's ecosystem. In other words, some have climate forcings.[5]

[5] A climate forcing is defined as a perturbation to the climate system in terms of a gas's radiative forcing. It also refers as a radiative forcing defined as a concept used for quantitative comparisons of the strength of different

Estimates of the climate forcings of the two representative pollutants: tropospheric ozone and sulfate/nitrate aerosols, have been well established. There have been many attempts to quantitatively assess climate sensitivity or a climate forcing of tropospheric ozone, and among the more recent estimates is 0.3 ± 0.15 W/m^2 (James Hansen, 2000). Compared to the estimates of the climate forcings of GHGs, the estimate of tropospheric ozone is not negligible as shown in Figure 7.

Sulfate and Nitrate aerosols also have negative climate forcings. Since the 1970s, anthropogenic aerosols have been caused by industrialization, urban air pollution, and mechanized agriculture (Hansen, 1990). It was initially argued that anthropogenic aerosols comprise about ~25% of all aerosols, on a global average, implying a climate forcing of 0.5-0.75 W/m^2, though measurements were unavailable (Hansen, 1990).

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human and natural agents in causing climate change by the IPCC. On the other hand, climate sensitivity is defined as a response of the climate system to the perturbation in terms of the change in annually averaged global mean surface temperature in ^{o}C per Wm^{-2} of global annual mean radiative forcing.

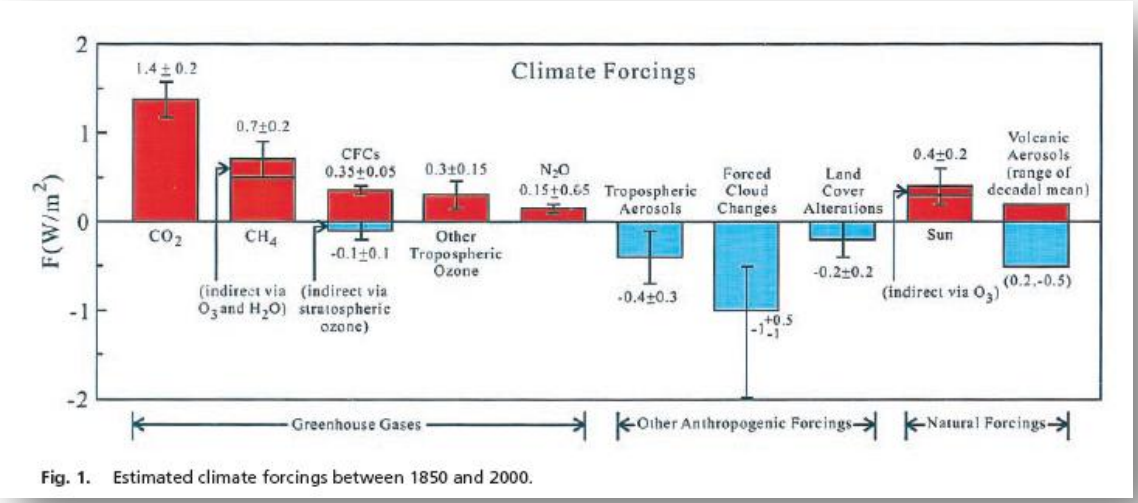


Fig. 1. Estimated climate forcings between 1850 and 2000.

Figure 7. Climate Forcings of GHGs and Air Pollutants

(Source: (James Hansen, 2000))

Black carbon (BC) in soot is also the dominant absorber of visible solar radiation, and since this species can be transported over long distances, its climate impacts should be significant (Carmichael, 2008). BC particles are not directly emitted, but originated from Particulate Matters (PMs). PMs are direct emissions from power plants or residential cooking stoves. Although PMs do not sustain in urban areas and are not transported at a global scale, they contribute to global warming through the production of BC. Hansen (2000) concludes that black carbon has a positive climate forcing, therefore, reinforcing global warming from human activity and reducing BC emissions will be effective in slowing the rate of climate change (James J. McCarthy, 2001). Jacobson (2002) argues that reducing BC emissions is valuable, but in some circumstances the reduction of the CO_2 emissions may be associated with an increase in the BC emissions and that an appropriate policy should be considered

(Jacobson, 2002). The IPCC estimates that the global mean radiation forcing of BC under the clear sky is $0.23 \pm 0.24 W/m^2$ (B. Metz O. D., 2007), which is approximately one third of the radiative forcing[6] of CO_2. While many efforts have sought to measure the climate forcing of BC, the degree of uncertainty is large. Ramanathan and Carmichael (2008) mention that uncertainty in the estimates is a factor of two to five at regional scales and at least $\pm 50\%$ at the global scale. It also implies that the distribution of climate forcing of BC is not homogeneous, which is due to the significant variability in BC emissions by region. Figure 8 clearly shows the regional heterogeneity of the distribution of BC emissions and its estimated climate forcings.

[6] The term, radiative forcing, is used equally as climate forcing.

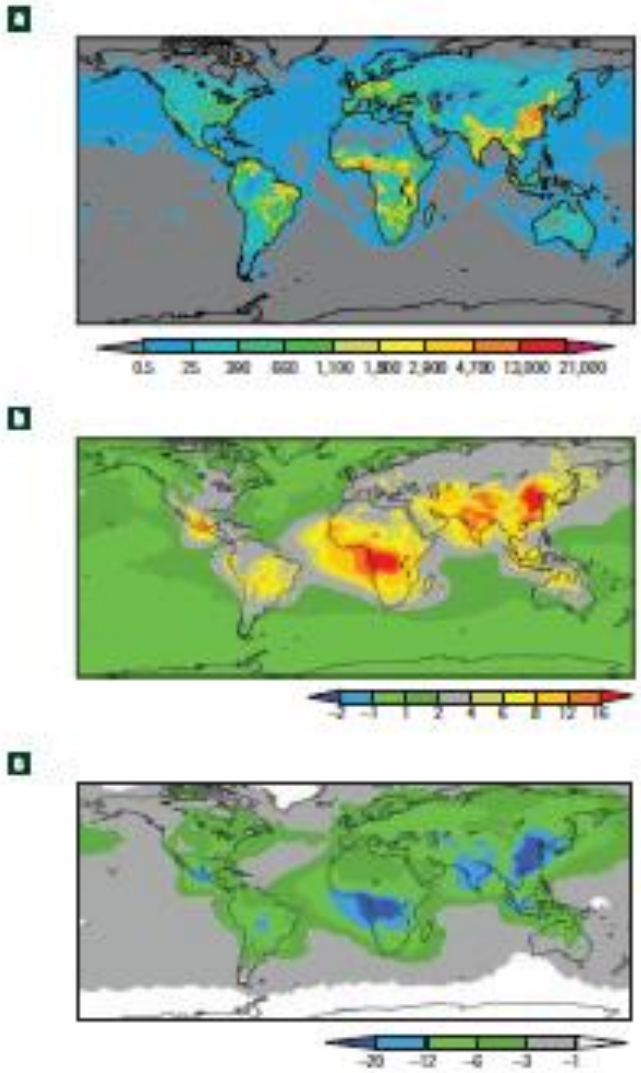


Figure 8: Global Distribution of BC Sources and Radiative Forcing.

Notes: Global distribution of BC sources and radiative forcing. **a**, BC emission strength in tons per year from a study by Bond *et al.*4, including emissions from fuel combustion (fossil fuels and biofuels) and open biomass burning (forest fires, savanna burning and outdoor cooking) for the year 1996. The uncertainty in regional emission is about ±100% or more. **b**, Atmospheric solar heating due to BC from the study by Chung *et al.*23 for the 2001 to 2003 period. This study integrates satellite aerosol data, surface network of aerosol remote sensing instruments and field observations with an aerosol-transport-chemical model and a radiative transfer model to obtain the forcing. Uncertainty in the forcing is ±30%. **c**, As in **b**, but for surface dimming due to ABCs. This shows the reduction in absorbed solar radiation at the surface by all anthropogenic aerosols (BC and non-BC) in ABCs. (Adopted from (Carmichael, 2008))

In response, the United Nations Environmental Programme (UNEP) has just launched a project aiming at assessing the roles of aerosols and proposing a policy on BC. In light of the policy, Ramanathan and Carmichael (2008) argue that the shorter lifetime of BC implies that short-term mitigation would be more effective, rather than long-term mitigation efforts.

2.1.6. Urban Air Pollution Control Policy

At present, most of the developed countries have already regulated urban air pollution through nationwide framework policies and by sector-specific control policies. This section summarizes the two types of policies in order to reveal the complexities between urban air pollution reduction and climate change mitigation.

Nationwide framework policies

Developed countries have already implemented guidelines or standards for controlling air quality in response to serious urban air pollution that arose during the 1970s'. For instance, the U.S. Clean Air Act[7](US.EPA, 2010), which is known as the most representative air pollution guideline, regulates the emissions of CO_2, NO_2, SO_2, and Particulate Matters (PMs) all over the United States. The Air Pollution Control Act of 1955 was the first federal

[7] The air pollution control act of 1955 was the first federal legislation involving air pollution, but the Clean Air Act of 1963 was the first federal legislation regarding air pollution control and then, the Air Quality Act was enacted in 1967. In 1970, the Clean Air Act was enacted, followed by the two major amendments done in 1977 and 1990 thereafter. USEPA retrieved on April 1st from http://www.epa.gov/air/caa/

legislation recognizing the risks of air pollution on public health and social welfare, followed by the first attempted legislation controlling air pollution, the Clean Air Act of 1967(US.EPA, 2010). In Europe, the United Kingdom has a much longer history of air pollution controls, showing an awareness of the health risks of air pollution. However, the Great Smog of 1952 in London, which is recognized as the worst air pollution event in British history, resulted in the first governmental air pollution legislation, the Clean Air Act of 1956 (AEA). Japan's first legislation regarding air pollution is the Air Pollution Control Law[8], controlling emissions of soot, smoke and particulate from the business activities of factories and buildings.

Sector-specific control policies

Due to the nature of urban air pollution– having relatively local impacts from specific emission sources, there are various guidelines or standards designed to address specific industrial facilities or other emission sources on top of the framework policies. For instance, the United States also has the Corporate Average Fuel Economy (CAFE), an emission regulation for vehicles. The United Kingdom also has the EU Air Quality Framework Directives[9] in addition to its own framework policy. The Netherlands has the NOx emission trading system designed to be consistent with the European Union Emission Trading System

[8] Law No. 97 of 1968. Latest Amendment by Law No. 32 of 1996. (Source: The Ministry of the Environment, Government of Japan)

[9] Directive 96/62/EC; Directive 99/30/EC, Directive 2000/69/EC, Directive 2002/3/EC.

(EU ETS).[10]. In Japan, various policy measures targeting different species or sectors have been implemented separately.

2.2. Framing Climate Change Issue

2.2.1. Causes of Climate Change - Emission Sources of Greenhouse Gases

The major source of GHG emissions is fossil fuel combustion, shared by the sources of urban air pollution. In 2007, the electricity generation (including heat), transportation, and industry sectors account for 41%, 23%, and 20% of the emissions of CO_2 respectively (IEA, 2009). Specifically, the share attributed to the electricity sector increased 14% from 1971 to 2007, and since the total amount of the CO_2 emissions also increased from 14.1 to 29.0 [Gt of CO_2], the contribution of electricity generation has increased more significantly. The impacts of global climate change varies widely due to factors such as the natural ecosystem and human activities, from globally to regionally, and to be more long term with greater uncertainty.

	1971		2007	
Sector	**CO_2 [Gt]**	**%**	**CO_2 [Gt]**	**%**
Electricity and Heat	3.807	27%	11.89	41%
Transportation	2.82	20%	6.67	23%
Industry	3.807	27%	5.8	20%
Residential	1.41	10%	1.74	6%
Others	2.256	16%	2.9	10%
Total	14.1	100%	29	100%

Table 1. CO_2 Emissions by Sector in 1971 and 2007
(Source: IEA, 2009)

[10] EUETS allows GHGs to be traded, aiming to implement the Kyoto Protocol.

2.2.2. Climate Change Mitigation

Climate change mitigation efforts have several aspects in light of the international-level, national or bilateral-level mitigation efforts, mitigation technologies, and the relevance to urban air pollution control policies. First, the 1992 UN Framework Convention on Climate Change (UNFCCC) developed an institutional structure for achieving the ultimate goal: the stabilization of the concentrations of GHGs. The ultimate objective of the UNFCCC is to achieve the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC). Its first comprehensive multinational effort is to implement a market-based policy, the Kyoto Protocol (KP)[11], which was agreed on in 1997 and entered into force in 2005. Since it determines the targets only until 2012, future mitigation options beyond 2010 have been discussed and there has been no clear direction proposed at the international level. For instance, in December 2009, the Conference of the Parties 15 (COP15) was held in Copenhagen, but no concrete mitigation options beyond 2012 had been agreed upon. Instead, it indicates a discrepancy of opinions on causes, impacts, and solutions of climate change between ANNEX I and non-ANNEX I[12] countries and even within each of the two groups. Contrary to dilemmas faced at the international level, national and bilateral-level mitigation actions have become increasingly common. These actions include the improvement of the

[11] The Kyoto Protocol to the United Nations Framework Convention on Climate Change

[12] http://unfccc.int/parties_and_observers/parties/non_annex_i/items/2833.php

energy efficiency of plants, fuel switching, renewable energy uptakes, and nuclear power uptakes to purely market-based options and so on. These details are not explored because they fall beyond the scope of the study.

2.3. Framing Thesis Questions

2.3.1. Introduction to Air-quality Co-benefits

The TAR of the IPCC defines the co-benefits as:

> *"The benefits of policies that are implemented for various reasons at the same time – including climate change mitigation – acknowledging that most policies addressing greenhouse gas mitigation have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity). The term co-impact is also used in a more generic sense to cover both the positive and negative side of the benefits. "* (B. Metz O. D., 2001)

A similar concept, "ancillary benefits," on the other hand, is defined by the TAR as:

> *"The ancillary, or side effects, of policies aimed exclusively at* ***climate change mitigation****. Such policies have an impact not only on* ***greenhouse gas emissions****, but also on resource use efficiency, like reduction in emissions of local and regional air pollutants associated with fossil fuel use, and on issues such as transportation,*

*agriculture, **land-use** practices, employment, and fuel security. Sometimes these benefits are referred to as "ancillary impacts" to reflect that in some cases the benefits may be negative. From the perspective of policies directed at abating local air pollution, **greenhouse gas mitigation** may also be considered an ancillary benefit, but these relationships are not considered in this assessment. See also **co-benefits**."*(B. Metz O. D., 2001)

A policy measure normally targets specific goals and both the costs and benefits associated with the policy measure may not include indirect impacts of the measure. In the thesis's context, however, since the major emission sources of urban air pollutants and GHGs are shared, a policy primarily targeting the mitigation of GHGs may indirectly constrain or increase the emissions of air pollutants. Adversely, an air pollution control policy may eventually contribute to the mitigation of GHGs.

An awareness of the indirect impacts of a policy on other areas did not rise until recently. In the first stage, the focused area of the relevant studies was primarily climate change mitigation and the other areas were assumed to be secondary or ancillary areas. The IPCC Second Assessment Report (SAR) suggested the further consideration of

"secondary-benefits[13]" of climate mitigation policies and also mentioned that the secondary environmental benefits might be substantial and that they were likely to differ from country to country (IPCC, 1995). Then, the TAR seriously argued in favor of the value of "co-benefits" of climate mitigation policies and urban air pollution policies (B. Metz O. D., 2001). The Fourth Assessment Report (FAR) also claims potential synergies and trade-offs of climate change mitigation policies with other policy areas including air pollution controls[14] (B. Metz O. D., 2007).

With respect to the scholarship, an increasing number of research papers have recently examined the co-benefits of the integration, or the ancillary benefits of long-term climate mitigation policies on urban air pollution mitigation in the near term (Pearce, 2000; Rob Swart, 2004; Pittel Rübbelke, 2008; G F Nemet, 2010).

Practically speaking, some governments have recently started considering co-benefits when designing their Clean Development Mechanism/Joint Implementation (CDM/JI) projects.

[13] The second assessment report mentions that secondary benefits include reductions in other pollutants jointly produced with greenhouse gases and the conservation of biological diversity. The second assessment report is retrieved from http://www.ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-assessment-en.pdf

[14] The TAR mentioned various types of the synergies and trade-offs in Chapter 11.8. http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch11s11-8.html

	Urban Air Pollution Control	Climate Change Policy
Mitigation Options	- End-of-pipe technologies - Fuel switching	- Regulations (taxes, emission standards, guidelines) - Market-based instruments (emission permits, emission trading)
Primary Benefits	Avoiding damages to public health, ecosystem, cultural heritages, etc.	- Reducing the concentrations of greenhouse gases
Ancillary benefits	(benefits depend on scenario, or policy options)	- Reducing other pollutants that are jointly produced with GHGs (mainly CO2, e.g. NOx, PM, SOx, etc.), which would result in improving public health - Reducing transportation-related damages such as traffic noise, road accidents, and community severance (e.g. loss of neighborhood due to heavy traffic flows) - Increasing the level of employment compared to that under baseline scenarios not adopting the climate policy - Stimulating technological innovations, deployment, and commercialization.

Table 2. Co-benefits in the intersection between urban air pollution and climate change mitigations

2.3.2. Statement of Thesis Questions

Under a broader policy impetus, the study addresses the following question:

"Could a climate policy be more effective in tandem with a technological or environmental policy?"

The issues over co-benefits essentially cover (1) quantitatively and qualitatively assessing scientific, economic, and political influences of global climate change on other areas and vice versa; (2) designing policy measures which integrate co-benefits; and (3) implementing them

in practice. To make a clear focus, the scope of the study is narrowed down as follows.

First, the study primarily focuses on the impacts of global climate change on urban air pollution from the scientific and the policy perspectives (denoted "air-quality co-benefits" or "ancillary effects"), and the impacts of urban air pollution on global climate are not explored.

Second, the study relates to (1), centering the scientific assessments that will base further discussions from an economic and policy viewpoint. The study does not provide original measurements of economic benefits or losses associated with co-benefits. Instead, the study reviews the effects of integrating air-quality co-benefits in policy options and examines implementation barriers.

Given the scopes as described, the study addresses the following questions.

I. What different impacts would a CO_2 stabilization policy have on urban air pollution in terms of species, regions, and the period of time?

II. What would be implied for policy design for integrating co-benefits?

III. What barriers to implementing air-quality co-benefits of the CO_2 stabilization policy would there be?

Chapter 3. Methodology

3.1. Outline

This thesis research is the first step of an ongoing research project with the ultimate purpose of linking a newly developed detailed model of urban-scale chemical and physical processing (Metamodel) (Cohen & Prinn, 2009) to the Massachusetts Institute of Technology (MIT) Integrated Global Systems Model (IGSM) Version 2.2 (A.P. Sokolov, 2005). The linkage will enable the sub-components of the IGSM, and the new Metamodel, to communicate interactively.

As a first step, the primary objective of this thesis research is to do a preliminary analysis by running the Metamodel in standalone mode by providing the data from the IGSM to the Metamodel exogenously. While the existing version of the IGSM has already included urban air pollution, the new Metamodel aims to extend the capabilities to describe the mechanism of urban air pollution more comprehensively as described in more detail later.

The first step starts with the economic sub-model of the IGSM, the Emissions Prediction and Policy Analysis Model (EPPA) (Sergey Paltsev, 2005). With a set of economic and policy

perturbations as inputs, the EPPA calculates emissions of air pollutants such as CO every 5 years. Then, the emissions of air pollutants from the EPPA go to the Metamodel. The Metamodel also takes some of the outputs from the other sub-models of the IGSM as its input variables such as temperatures, elevations, precipitation, and the background concentrations in urban areas. Then, the Metamodel simulates a mole fraction and mass flux of each selected air pollutant including aerosols.

3.2. MIT Integrated Global Systems Model (IGSM)

The MIT IGSM Version 2.2 aims to model the physical and chemical feedbacks within the Earth's natural system and their interactions with human activities (A.P. Sokolov, 2005) . The IGSM includes (1) a two-dimensional global atmospheric statistical-dynamics model that also includes the key physical (e.g. clouds and precipitation) and atmospheric chemistry processes, and the urban airshed model is linked into; (2) an ocean circulation model; and (3) a global, terrestrial water, energy, and ecologic model system consisting of the Community Land Model (CLM), the Terrestrial Ecosystems Model (TEM), and the Natural Emissions Model (NEM). These models within the IGSM are also linked to the MIT Emissions Prediction and Policy Analysis (EPPA) model. Since the IGSM is 2-dimentional (46 latitude bands and 11 levels of heights), the data taken from the IGSM, or from some sub-models of the IGSM, has to be modified so that they can fit with the data required by the Metamodel.

3.3. MIT Emissions Prediction and Policy Analysis (EPPA) model

The EPPA model is a computable general equilibrium (CGE) model of the world economy developed by the MIT Joint Program on the Science and Policy of Global Change (Sergey Paltsev, 2005), which calculates economic activities and associated emissions of GHGs and air pollutants. It is recursive-dynamic and has 16 regions. The economic data exogenously relies on the Global Trade, Assistance and Production (GTAP) dataset (Dimaranan and McDougall 2002), which accommodates a consistent representation of regional macroeconomic consumption, production and bilateral trade flows. The energy data in physical units are based on energy balances from the International Energy Agency. Among the variables produced by the EPPA model, the Metamodel uses the data of the emissions of 8 air pollutants (CO, NOx, VOC, O_3, SO_2, NH_3, BC, and OC) and the distribution of the 16 regional codes by countries as the Metamodel assigns each of the 4 types of the sub-metamodels to each country.

3.4. New Metamodel

The Metamodel represents chemical and physical processes in urban areas, which is separately modeled as its processing is far more complicated than the global atmospheric model. The detail features are described below.

3.4.1. Modeling Urban Air Chemical and Physical Processing

Because the features of air pollution vary city by city, there are many complexities in modeling urban air pollution. First, anthropogenic activities are unique to each city, because of the differences in the status of the economic development resulting from technological, economic, political factors, and even differences in people's preferences and behaviors, all of which cause non-linearity in types of species, the levels of emissions, and the temporal and spatial differences in the behaviors of these species. This non-linearity causes significant uncertainty and variability in describing and predicting chemical and physical processes. Therefore, existing models, especially those which can simulate photochemical processes associated with urban air pollution, must represent these environments at a very detailed level and thus at a large computational expense. Among the major existing photochemical models such as the Urban Airshed Model (UAM-V), the Regional Modeling System for Aerosols and Deposition (REMSAD), the Community Multi-scale Air Quality (CAMQ), and the Comrehensive Air Quality Model (with extension) (CAMx), the Metamodel is derived from the CAMx as a reduced-form model. The reduced-form model can reduce the computation time significantly, performing simulations of urban air chemical and physical processes, while its simulation mechanism follows approaches of the CAMx. The approaches adopted by the CAMx are described below.

3.4.2. The Comprehensive Air quality Model with eXtensions (CAMx)

The CAMx is an Eulerian photochemical dispersion model that simulates the emission, dispersion, chemical reaction, and removal of pollutants in the troposphere by solving the pollutant continuity equation for each chemical species (l) on a system of nested three-dimensional grids. The following Eulerian continuity equation describes the time dependency of the average species concentration (c_l) within each grid cell volume as a sum of all of the physical and chemical processes operating on that volume (ENVIRON, 2010). The equation is:

$$\frac{\partial c_l}{\partial t} = -\nabla H \cdot V_H \cdot c_l + \left[\frac{\partial (c_l \cdot \eta)}{\partial z} - c_l \cdot \frac{\partial}{\partial z} \cdot \left(\frac{\partial h}{\partial t}\right)\right] + \nabla \cdot \rho \mathcal{K} \nabla (c_l/\rho) + \frac{\partial c_l}{\partial t}(Emission) + \frac{\partial c_l}{\partial t}(Chemistry) + \frac{\partial c_l}{\partial t}(Removal)$$

where c_l is the average species concentrations, V_h is the horizontal wind vector, η is the net vertical entrainment rate, h is the layer interface height, ρ is atmospheric density, and K is the turbulent exchange (or diffusion) coefficient. The term on the left side represents the time dependency of the average species concentrations. On the right hand, the first three terms represent the diffusion and transport of the species. Namely, the first term represents the horizontal advection, the second term represents net resolved vertical transport across an arbitrary space- and time-varying height grid, and the third term represents sub-grid scale

turbulent diffusion. The rest of the three terms on the right hand represents the time dependency of the emissions of the species, chemical reactions relevant to each species, and the removal processes through dry surface uptake/deposition and wet scavenging by precipitation (ENVIRON, 2010). To solve the continuity equation, the CAMx includes peer-accepted algorithms and component formulations. The six components in the equation are treated as summarized below.

Horizontal Advection

The horizontal advection performs based on the area preserving flux-form advection solver of Bott (1989) or the Piecewise Parabolic Method (PPM) of Colella and Woodward (1984) as implemented by Odman and Ingram (1993).

Vertical Transport (Advection and diffusion)

The transport algorithm is mass conservative, consistent, and does not allow any loss and gain of mass. To follow the mass conservation rule, the concentrations of each species, both trace gases and aerosols, is treated as a density and the equations of the advection and diffusion are solved in flux form.

Turbulent Diffusion

The turbulent diffusion in the vertical direction performs based on simple K-theory first-order closure approaches in the CAMx. In the CAMx, K-theory only treats mass transfer "cell-by-cell" in the horizontal direction or "layer-by-layer" in the vertical direction.

Emissions

Emissions of the pollutants are assumed to be emitted near the ground surface at the center of the horizontal direction and that are not sufficiently buoyant to reach into the upper layers of the Metamodel. Also, the emissions are exogenously provided.

Chemical Reactions

The CAMx includes both gas-phase and aerosol-phase chemistry. In particular, the chemical reaction mechanisms in the CAMx include PAN chemistry, radical-radical termination reactions, isoprene chemistry, and secondary organic aerosol formation from condensable gases, aqueous PM chemistry, inorganic PM thermodynamics, and aerosol size evolution.

Removal Processes

There are two removal processes: dry deposition which is the diffusion of the species to the ground surface and uptake into the ecosystem such as absorption by plants and wet deposition

which refers to the uptake of the species by rainfall or cloud. Regarding wet deposition, a particle becomes a nucleus forming a cloud droplet with water molecules in the air and the droplet is removed by precipitation or wind from the air, of which degree depends on the precipitation rate or the size of the droplet. Conversely, dry deposition involves more complicated processes. It includes the reactivity, solubility, and diffusivity of gases, the sizes of particles (or aerosols), metrological conditions and surface characteristics. Based on the above understanding, the next section describes the overall structure of the Metamodel derived from the CAMx.

3.4.3. The Structure of the Metamodel

For the purpose of the efficiency of the calculation, the Metamodel is derived by parameterizing the CAMx by using the Probability Collocation Method (Tatang, 1997).

Parameterization by the Probability Collocation Method

The general collocation method is a mathematical technique for reducing a model to a simpler form for the purpose of reducing the computation time. The probability collocation method is, in particular, designed to approximate the response of the model as a polynomial function of uncertain parameters (Webster, 1996). In this case, the outputs, y_i, are the concentrations or the fluxes of mass of the species predicted by the Metamodel and the inputs,

x_i, are some of the initial values, which are selected to derive the Metamodel by approximating the CAMx (Tatang, 1997).

$$y_i = f\left(x_j\right) \ (i = 1, \ldots., K;\ j = 1, \ldots., N)$$

Following the variational approach, each y_i can be approximated by using a set of specified functions $\{g_i(x_j)\}$, of x_j

$$\widehat{y_i} = \sum_{i=1}^{N} y_i g_i(x_j)$$

where N is the order of the approximation. Since the approximation of y_i may not simulate the actual model, the residual of the model is defined as below.

$$R(\{y_i\}, x_j) = \widehat{y_i}(x_j) - y_i(x_j)$$

The set of the coefficients in the approximation of $\{y_i\}$ can be calculated by requiring the residual and each of $\{y_i\}$ should be orthogonal to each other as expressed below.

$$\int_x R(\{y_i\}, x_j) \cdot g_i(x_j) dx_j = 0 \ (j = 1, N)$$

By using the Gaussian quadrature approximation, the above equation can be solved as below

$$\int_x R(\{y_i\}, x_j) \cdot g_i(x_j) dx_j \simeq \sum_{j=1}^{N} v_j \cdot R(\{y_i\}, x_j) \cdot g_i(x_j)$$

Where v_j are the weights. If v_j and $g_i(x_j)$ have the same sign and are not zero for all i and j, the equation can be approximated by the following:

$$R(\{y_i\}, x_j) = 0, (j = 1, N)$$

which derives the coefficients $\{y_i\}$ of the approximation of the CAMx, in other words, the coefficients for the polynomial expansion of the CAMx.

Specifically, noted that for deriving the Metamodel, since each input variable x_j has a certain range of the variability, it is treated as a probability density function (PDF) and each output variable is also treated as a PDF and that the variational approach used here is the polynomial chaos expansion. Therefore, $\{g_i(x_j)\}$ is the set of coefficients for the orthogonal polynomials for the set of the input variables $\{x_j\}$.

Subcomponents of the Metamodel

The Metamodel includes the four region-specific metamodels constructed to model the processing in China, India, developed countries, and developing countries respectively. In addition, each of the four region-specific Metamodels has the four different sub-metamodels according to metrological conditions. The underlying reason for having the sixteen different metamodels lies in the significant variability of the features of cities in addition to the high difficulties and complexities in solving the continuity equation. Therefore, to simplify the calculation, the Metamodel is divided into the sixteen different types, applying some assumptions, which determine which metamodels should be applied for each city.

3.4.4. Dealing with Regional Variety

The Metamodel has the four different sub-metamodels; China, India, Developed, and Developing metamodels. The rationale of doing so is that, since the values of the primary emissions vary widely by cities due to the differences in the proportions and the variety of emission sources and differences in technologies, they should be differentiated when the emissions of the primary emitted species other than CO and BC are determined subject to the emissions of CO or BC.

3.4.5. Dealing with Meteorological Variety

The continuity equation applied by the CAMx requires substantial computation time. To make the simulation feasible and efficient, four meteorologically different scenarios are utilized within the Metamodel. The scenarios are identified by the amount of liquid water in the form of rain, the amount of cloud cover, and the mass flux of air integrated over all four sides and the top of the urban area through the boundaries of the urban area. The criteria for these three variables are described below.

Meteorological Scenario	Rainfall [mg/m^3]	Mass Flux of Air [109 kg/s]	Cloudiness [%]
Scenario A	241.0	4.56	62.8
Scenario B	0.00	4.38	4.38
Scenario C	21.5	5.70	5.70
Scenario D	1.72	1.61	1.61

Table 3. The Four Meteorological Scenarios within the Metamodel

Note:

(1) Scenario A represents R241-C63-W46, Scenario B represents R000-F00-W44, Scenario C represents R021-F19-W57, and Scenario D represents R002-F02-W16 described in Jason et al. (2009).

(2) The set of the values of rainfall, mass flux of air, and cloudiness for Scenario A, B, C, or D is used to run the Metamodel under each meteorological scenario.

More intuitively, scenario A represents the meteorological conditions of heavy rainfall, frequent cloud cover, and relative windiness. Scenario B represents the meteorological conditions where the weather is completely dry, relatively windy, and it is covered by some clouds (partly-cloudy). Scenario C represents the meteorological conditions where it is moderately rainy, cloudy, but highly windy. Finally, the scenario D represents the conditions where it is little rain, clear, and stable weather.

In reality, the daily meteorological conditions in a city do not necessarily fall into one of the 4 scenarios but would be a combination of the four. Therefore, every time the Metamodel is run, it calculates the outputs under the four scenarios respectively, and the final results (mole fractions and mass fluxes) for a city are the weighted average of the four scenarios.

3.4.6. The Input Variables

The set of the input variables for the Metamodel are selected to sufficiently parameterize the CAMx. As discussed before, each of the input variables is treated as a PDF to make the Metamodel more robust and flexible in the variety of the input values. The inputs specifically used to derive the Metamodel are the Day of the Year; the geographic latitude of urban area; temporal weight which determines the temporal variety of the emissions; spatial distance which represents the extent to which the emissions are condensed; the daily average temperature; the diurnal temperature, which is the difference between the maximum and minimum temperatures; emissions of CO, VOC, NOx, Black Carbon (BC), SO_2, NH_3, and Organic Carbon (OC); and boundary concentrations of O_3, CO, NOx, SO_2 and Isoprene. Each of the PDFs is derived based on the values estimated by the MIT EPPA model or the MIT IGSM over future decades until the year 2100. The types of the PDFs are defined in the following Table and the definitions of the PDFs are:

Unifrom $(a \le x \le b)$: $f(x) = \dfrac{1}{b-a}$

Beta $(a \le x \le b; p, q > 0)$: $f(x)$

$$= [(x-a)^{p-q}(b-x)^{q-1}] \cdot \left[\left(\int_0^1 t^{p-1}(1-t)^{q-1}\,dt\right)((b-a)^{p+q-1})\right]$$

Lognormal $(x, m, \sigma > 0)$: $f(x) = \dfrac{exp\left(-\left(ln\left(\frac{x}{m}\right)\right)^2/(2\sigma^2)\right)^2}{x\sigma\sqrt{(2\pi)}}$

Fixed : $f(x) = xS$

Where *x* is the input value, and a,b,p,q,m,σ, and S are the parameters used to describe the form of the distribution function (Table 4).

Input Variables	**Type of PDF**
Day of the Year [Days]	Uniform
Geographic Latitude of Urban Area [degree]	Beta
Temporal Weight	Uniform
Spatial Distance [km]	Uniform
Daily Average Temperature [K]	Beta
Diurnal Temperature [K]	Beta
Emission Values: CO [ton/day]	Lognormal
VOC [ton/day]	Fixed
NOx [ton/day]	Fixed
BC [ton/day]	Lognormal
SO2 [ton/day]	Fixed
NH3 [ton/day]	Fixed
OC [ton/day]	Fixed
Boundary Values: O3 [ppb]	Lognormal
CO [ppb]	Lognormal
NOx [ppt]	Lognormal
SO2 [ppt]	Lognormal
Isoprene [ppt]	Lognormal

Table 4. The Input Variables and the parameters of the PDFs
(Source: **(Cohen & Prinn, 2009)**)

It should be noted that the emissions of CO and BC from the EPPA model are used to run the Metamodel and the emissions of the rest of the species, VOC, NOx, NH_3, SO_2, and OC are used to calculate the flux of mass in the post-processing of the Metamodel.

3.4.7. The Output Variables

The output species from the Metamodel are 17 trace gases - O_3, CO, NO, NO_2, N_xO_y, HNO_3, SO_2, H_2SO_4, HCHO, CH_3CHO, Toluene, Xylene, C_2H_4, C_2H_6, PAN, H_2O_2, NH_3 - and 4 aerosols species – sulfate aerosols (SO_4=), Black Carbon (BC), Organic Carbon (OC), and Nitrate aerosols (NO_3-). For each output species, the Metamodel produces the mole fraction (or concentration) ([ppm] for trace gases and [ug/m^3] for aerosols), and the flux of mass [kg/day]. For the 4 aerosol species, the Metamodel also projects the numbers of aerosols [/m^3]. Note that the concentrations are the daily-average values, and the mass fluxes are the net fluxes at the end of a day. All of the outputs are the values in a grid by 1x1 degree in a horizontal direction and over the bottom three vertical layers of the urban area, which is approximately 100 meters.

3.5. Linking Urban Air Chemical and Physical Processing to the IGSM

First of all, the development of linking the Metamodel to the IGSM has not been completed yet and the version used throughout this chapter works only in stand-alone mode, that is, the Metamodel is forced exogenously by all the required inputs (noted above) and the mole fractions and net exchanges are not (as yet) passed back into the atmospheric model of the IGSM. Nevertheless, the following description associated with the development of the linkage is provided as a guide for further development.

3.5.1. Linking to the EPPA model

First, among the species used by the Metamodel, only CO and BC are critical to determine the emission values of the other species, as they determine the emissions of VOC, NOx, SO_2, NH_3, and OC based on the assumptions that the first two species are proportional to the emissions of CO and the remaining 3 species are proportional to the emissions of BC at certain ratios for each city (Cohen & Prinn, 2009). Although these ratios are already embedded in the Metamodel itself, it is important to realize that, unlike the previous urban air shed model, the new Metamodel no longer requires the emissions of species other than CO and BC as input emission values.

Second, since the EPPA model predicts the anthropogenic emissions by countries, we need to distribute the emissions to each 1x1 degree grid cell. The way we are going to distribute the emissions is still under development; for this implementation, the currently used criterion in which the Metamodel recognizes an urban grid is used, and requires the emissions of NOx are greater than 5kgN/day/km^2. This also ensures that we maintain the same total number of cities for the globe as in the current version of the IGSM, which will allow for more effective comparisons and evaluation with the upgraded, fully-coupled IGSM.

Third, we need to create daily emissions data from the annually-based EPPA emission data, which is derived by dividing the annual emissions by 365 days. While there should be seasonal variations in the emissions, the Metamodel assumes that the emissions keep constant over the course of the year. This is most likely an unrealistic prescription for many cities across the globe, and further work should be considered to explore the impact of this model implementation within the fully coupled environment.

Fourth, the EPPA model provides the regional codes with the Metamodel, which will be described in the later section.

3.5.2. Linking the Metamodel to the CLM

The CLM provides zonal data of daily average temperatures, daily minimum temperatures, daily maximum temperatures, wind speeds, and precipitation - all of which are needed every time a Metamodel is run for a city.

These data are also the functions of the dominant vegetation types. As described in Table 5, there are 17 types in addition to the ocean (0). Each 1x1 degree grid cell is assigned to the most dominant land cover of the 17 types (Fig. 9) or 0; therefore, it can determine the appropriate values for the 5 variables.

Index	Type of Vegetation
0	Ocean
1	bare soil
2	needleleaf_evergreen_temperate_tree
3	needleleaf_evergreen_boreal_tree
4	needleleaf_deciduous_boreal_tree
5	broadleaf_evergreen_tropical_tree
6	broadleaf_evergreen_temperate_tree
7	broadleaf_deciduous_tropical_tree
8	broadleaf_deciduous_temperate_tree
9	broadleaf_deciduous_boreal_tree
10	broadleaf_evergreen_shrub
11	broadleaf_deciduous_temperate_shrub
12	broadleaf_deciduous_boreal_shrub
13	c3_arctic_grass
14	c3_non-arctic_grass
15	c4_grass
16	Corn
17	Wheat

Table 5. The Dominant Vegetation Types

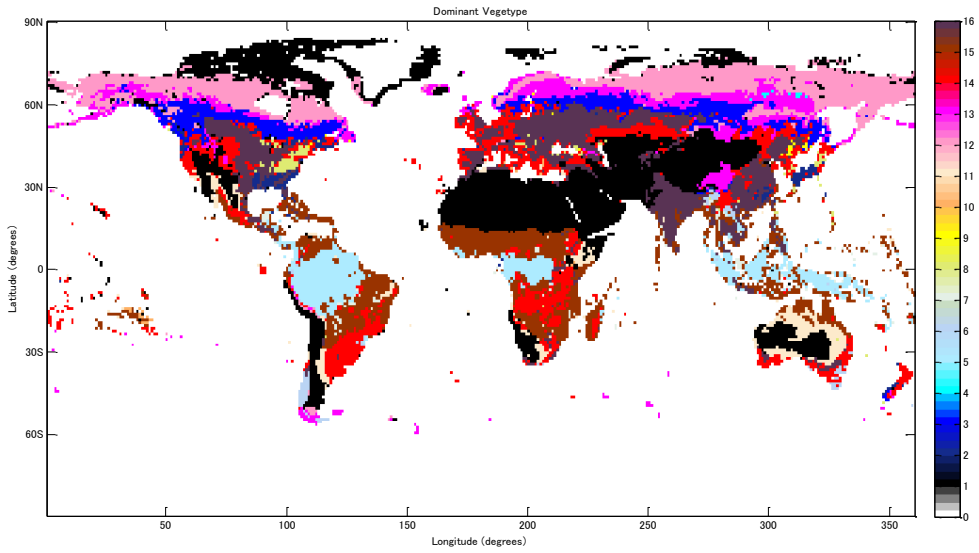


Figure 9. The Distribution of the Dominant Vegetation Types adopted by this thesis

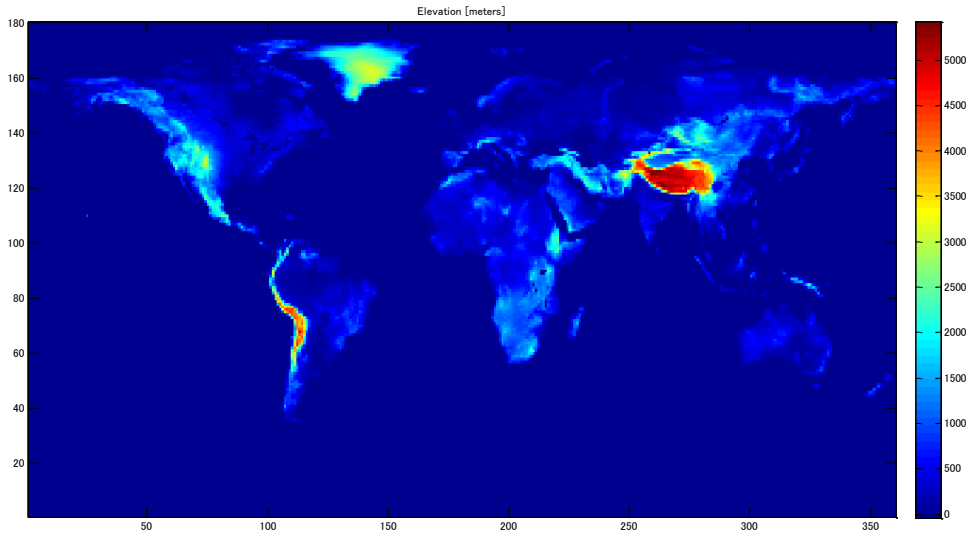


Figure 10. Elevations

3.5.3. Linking the Metamodel to the global atmospheric chemistry model

The Metamodel calculates the urban air chemical and physical processes in a 3-dimensional box, and the box requires the boundary values of the concentrations of O_3, CO, NOx, SO_2, and Isoprene on a daily basis. Since the Metamodel is supposed to be embedded in the global atmospheric chemistry model, its boundary values should be consistent with the values predicted by the global atmospheric chemistry model. To link the two models, several technical efforts have been made.

First, the boundary values predicted by the global atmospheric chemistry model are in two dimensions, which mean that the concentrations of the species are the same across each of the 46 latitude bands and that they vary vertically (the IGSM has the 11 vertical layers). On the other hand, each city needs one single 1x1 degree value horizontally as well as vertically.

Therefore, we assume that the boundary values for each city take those of the corresponding latitude band averaged over the bottom 3 vertical layers multiplied by a certain coefficient, thus contrasting the values over the land with those over the ocean.

The reason why we have taken into account the differences in the boundary values over the land and the ocean is because all of the species we need are emitted from the land and relatively short-lived, which would indicate that these species are unlikely to spread out uniformly across latitude bands and the concentrations over the ocean would be relatively lower. This assumption could be justified by viewing the concentrations predicted by the CAMx [15]. Technically, the coefficients are created by using the monthly averaged concentrations averaged over 10 years in order to reduce the influences of the interannual variability of the predicted values.

Second, the global model can give only the monthly average data, though the Metamodel needs daily data. Therefore, we assume that the boundary values remain constant over each month.

[15] The concentrations of O3, CO, NOx, and SO2 are not publically available, but provided through the courtesy of Dr. Chien C.Wang.

Third, the boundary values of Isoprene are not predicted by the global atmospheric chemistry model. Therefore, we use the monthly averaged concentrations of Isoprene predicted directly by the Community Atmospheric Model (CAM)[16] by assuming this remains constant over the years. In using the CAM data, another technical assumption we have made is that all 1x1 degree grid cells of the Metamodel are the same as the value in a 2.5x2 degree grid cell of the CAM. To reduce the influences of the interannual variability of the concentrations, the values are averaged over 3 years.

3.5.4. Assigning the Region-specific sub-metamodels

The EPPA model categorizes all countries into 16 regions as shown in the Table below. The Metamodel allows any cities within Australia, New Zealand, Canada, the European Union, Japan and the United States to use the Developed metamodel over the years and forces cities in other countries, except those in China and India, to utilize the Developing metamodel over the years. Obviously, any cities in China and India utilize the China and India metamodels respectively.

The first assumption for the categorization we have made in the offline version is that each country or region remains categorized in the same sub-metamodel, which may not be true in

[16] The concentrations of Isoprene are also provided by Dr. Chien C.Wang.

the future. For instance, given the fact that China's economy has been rapidly developing, it may become a developed country in the future. The same is true of India.

The second assumption is that all of the countries categorized into the ASI group use the Developing metamodel, though it is more reasonable to consider Korea and Singapore as developed countries. To make it possible to treat the two countries separately from the others in the ASI group, we need to label any potential cities in both countries exactly by latitude and longitude every year for the whole 21th century. It may be possible if we use the same cities for future years. However, the preliminary offline version of this IGSM-Metamodel did not do so, because it will be expanded in the future ideally in a way that it allows any grids to become new cities from certain years in the future if they meet criteria in identifying urban areas. In this regard, future online versions should be done so that it does not narrow the flexibility of the linkage between the Metamodel and the IGSM.

Regional #	Country/Region	Type of Metamodel Used
1	AFR (Africa)	Developing
2	ANZ (Australia & New Zealand)	Developed
3	ASI (Higher Income East Asia)	Developing
4	CAN (Canada)	Developed
5	CHN (China)	China
6	EET (Eastern Europe)	Developing
7	EUR (European Union)	Developed
8	FSU (Former Soviet Union)	Developing
9	IDZ (Indonesia)	Developing
10	IND (India)	India
11	JPN (Japan)	Developed
12	LAM (Central & South America)	Developing
13	MES (Middle East)	Developing
14	MEX (Mexico)	Developing
15	ROW (Rest of World)	Developing
16	USA (United States)	Developed

Table 6. List of the Regions Defined in the EPPA model

Note:

(1) EUR includes the European Union (EU-15) and countries of the European Free Trade Area (Norway, Switzerland, Iceland)

(2) EET includes Hungary, Poland, Bulgaria, Czech Republic, Romania, Slovakia, Slovenia

(3) FSU includes Russia and Ukraine, Latvia, Lithuania and Estonia (which are included in Annex B) and Azerbaijan, Armenia, Belarus,Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan (which are not)

(4) ASI includes South Korea, Malaysia, Philippines, Singapore, Taiwan, Thailand

(5) ROW includes all countries not included elsewhere: Turkey, and mostly Asian countries

Chapter 4. Preliminary Assessment of Impacts of Climate Policy on Urban Air Pollution

4.1. Scenarios

The study uses two scenarios; a no policy case and a stabilization policy.

1) The no policy case is a reference scenario that portrays no GHG stabilization policies will be adopted during the 21st century. It also uses median parameter values for the IGSM climate and economic model components (Sokolov et al., 2009).
2) The stabilization policy assumes constraints on CO_2 and other trace-gas emissions at levels consistent with a global target of stabilizing atmospheric concentrations at 450 parts per million (PPM) by 2100 or CO_2-equivalent atmospheric concentrations at 550PPM (Webster et al., 2010). The EPPA model within the IGSM assumes that each country takes necessary actions to achieve the target by 2100.

The analyses that follow present the responses of mole fractions and mass fluxes of key urban air pollutants to changes in the emissions affected by the 450ppm policy as well as to the changes associated with the ecological, meteorological, and geological characteristics.

4.2. Assumptions and Model Configurations

The assumptions used specifically throughout the analyses in Chapter 4 are summarized as below.

1) The base year is 1997 and the emissions of the species input to the Metamodel are calculated by scaling the emissions at the base year according to the corresponding projections of the no-policy (Sokolov et al., 2009) and 450 PPM policy (Webster et al., 2010) scenarios. Emissions for each city are scaled according to its corresponding EPPA region, which are calculated from the base year, 1997 to 2100 every 5 years[17].
2) The analyses herein do not consider the situation in which any developing nation (i.e. China and India) would transition into a "developed" nation through the course of the 21st century. Thus, for these numerical experiments, China and India are assigned to their respective metamodels, which are calibrated for contemporary conditions, throughout the 21st century for all scenarios.
3) The number of urban grids does not change over years under the present technical constraints, though in reality urban areas are likely to increase in number for some areas (and potentially decrease in other regions) during the course of the 21st century. As such, this updated version of the Metamodel, as in the previous version of the IGSM, deems a grid point as an urban environment, if they have the NOx emissions

[17] The EPPA model estimates the emissions in 1997, 2000, and after 2001, it estimates the values every 5 years.

exceeding 5kg of Nitrogen per day per km^2 ($5kgN/day/km^2$). This determination is only performed for the base year of the simulations.

For this study, the updated version of the Metamodel has not been dynamically linked to the IGSM. Thus, all of the input values in the IGSM for the whole period of time are not influenced by the outputs from the Metamodel. For instance, the meteorological IGSM variables such as daily mean, maximum, and minimum temperatures in the 2^{nd} year do not consider the impacts of the changes in the mass fluxes of the urban air pollutants due to the addition of the detailed urban chemical and physical processes. This dynamically linked configuration must be employed for fully integrated investigations of climate and air-quality policies. Nevertheless, a necessary first step in constructing any credible coupled modeled system such as that requires an evaluation and characterization of the sub-model augments. This study fulfills this need by examining the performance of the updated MetaModel at simulating the contemporary conditions of urban environments as well as characterizing its response to changing climate and global emissions - forced by IGSM atmospheric conditions and emissions.

4.3. Inputs

4.3.1. Identification of Urban Areas

As introduced in Section 4.2., urban areas are identified by the NOx emissions for the year of 1997 predicted by the EPPA model. Figure 11 is a 1-by-1-degree global map of cities, which shows most of the cities identified are located in Europe, East Asia, and Northern America and there are few cities identified in Africa, Russia, Middle East, Southern America, Australia, and New Zealand. While the total number of cities is 500, 478 cities are located in the northern hemisphere. Also, from Figure 12, we can see that urban areas are identified specifically in the latitudes from 36.5^{o}S through 60.5^{o}N and that there are latitude bands where no city exists even between 36.5˚S and 60.5˚N.

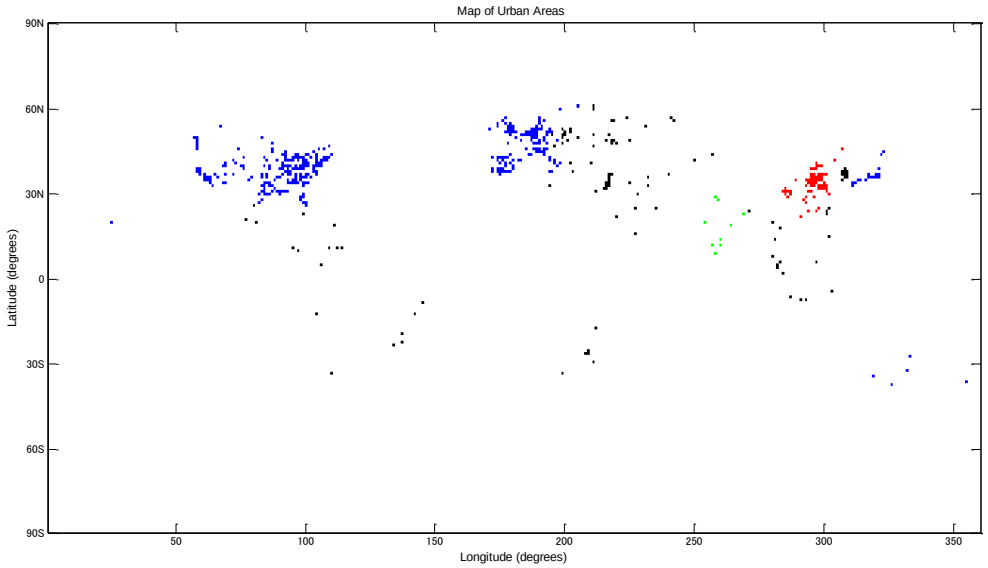


Figure 11. Identification of urban areas adopted by this thesis
(Note: The blue dots denote cities in developed countries, the black dots denote cities in developing countries, the red dots denote cities in China, and the green dots denote cities in India.)

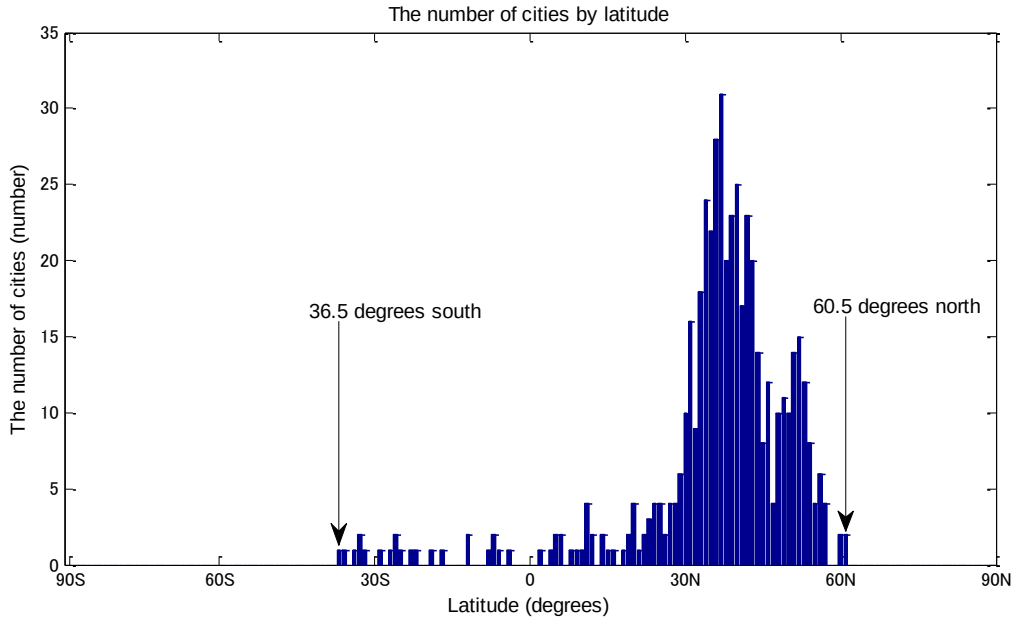
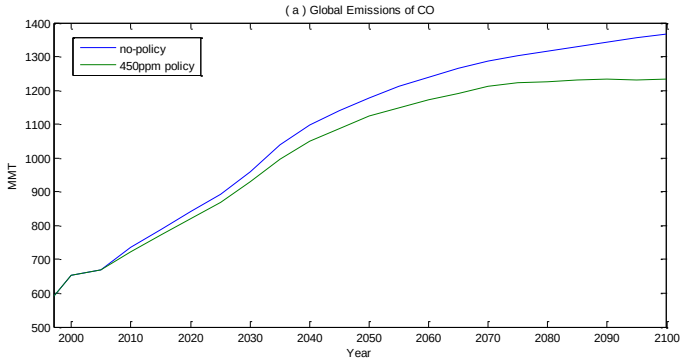
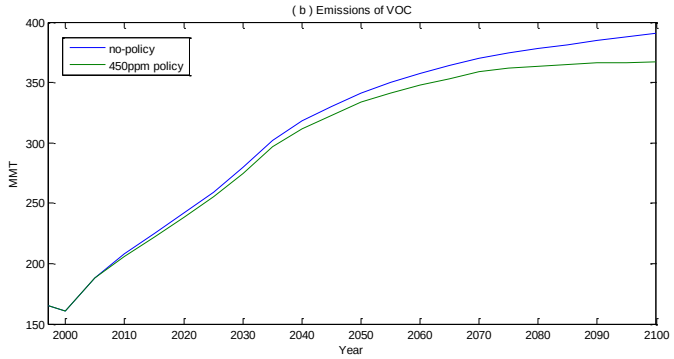


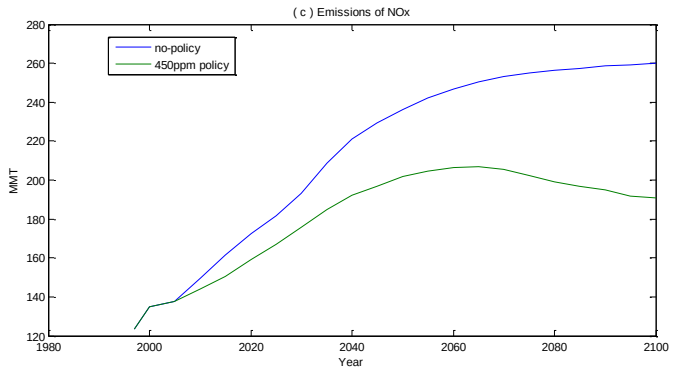
Figure 12. The Number of cities by latitude for the period from 2001 through 2100

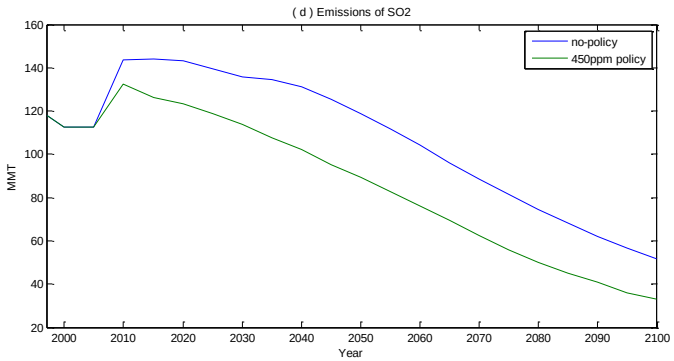
4.3.2. The Global EPPA Emissions

Figure 13 shows the global emissions of CO (Figure 13a), VOC (Figure 13b), NOx (Figure 13c), SO_2 (Figure 13d), BC (Figure 13e), and OC (Figure 13f) for the 21st century, calculated by the EPPA model. First, for the no-policy case, the global emissions of CO, VOC, and NOx become more than double by 2100, though the increasing rates are declining for the years subsequent to 2050. On the other hand, SO_2, BC, and OC are expected to be more than halved for the 21th century. For the 450ppm policy case, the global emissions of CO and VOC are also increasing, but the emissions will become slightly lower than those for the no-policy case by 2100. In addition, the global emissions of NOx will increase roughly until 2060, then decrease for the remainder of the 21th century. As for SO_2, BC, and OC, the global emissions will decline.


(a) Global Emissions of CO
no-policy
450ppm policy
MMT
Year


(b) Emissions of VOC
no-policy
450ppm policy
MMT
Year


(c) Emissions of NOx
no-policy
450ppm policy
MMT
Year


(d) Emissions of SO2
no-policy
450ppm policy
MMT
Year

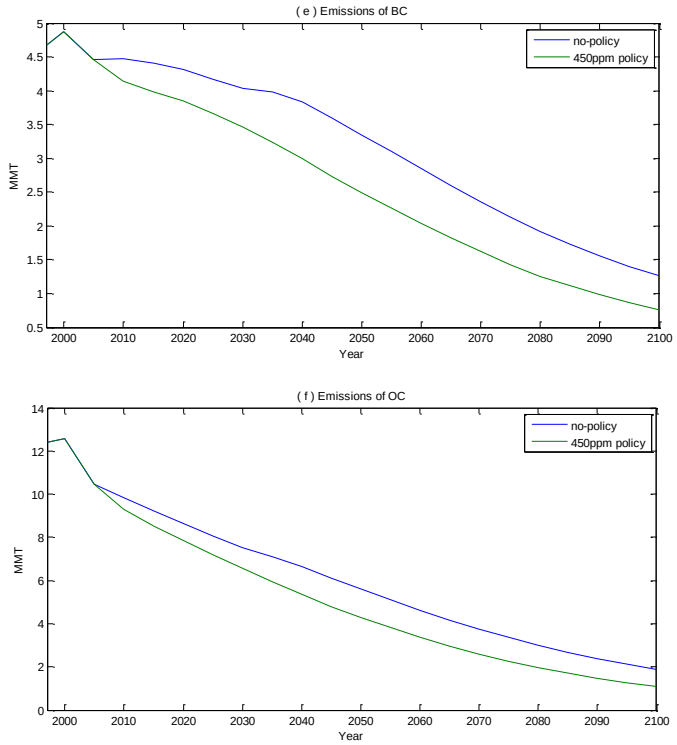


Figure 13. The global emissions predicted by the EPPA model: (a) CO; (b) VOC; (c) NOx; (d) SO2; (e) BC; and (f) OC

4.4. Impacts of the 450ppm Policy on Global-Scale Urban Air Pollution

4.4.1. Validity of Data

Before analyzing global-scale data, we need to check whether each output value is reasonably calculated by the Metamodel. We observe that the results for some cities are not predicted well by the Metamodel. Specifically for ANZ, i.e., Australia and New Zealand, the results for CO, NO_2, HCHO, and BC are unreasonably low for both the no-policy case as well as the 450ppm policy case. The cities in the region identified by the Metamodel are located in the latitudes of between 36.5^{o}S and 26.5^{o}S. The input values of daily emissions of BC for urban grids in ANZ are too small to fall into the range that the Metamodel can work appropriately

(Section 3.4.6 and Table 4). Figure 14 shows the lines representing the best lognormal fits of the daily emissions of BC over each city in ANZ estimated by the EPPA model for the no-policy and 450ppm policy cases. It shows the daily emissions of BC in ANZ are between 0.5 [ton/day] to 4 [ton/day]. However, the Metamodel requires values of emissions of BC to be approximately between 4 [ton/day] to 1,000 [ton/day], larger than the actual input values.

As for the other inappropriate results for the whole period, although we have not clarified why the outputs, i.e., monthly mean concentrations, are inappropriate, the reasons would be emissions of CO and BC, daily mean temperatures, diurnal temperatures, as well as boundary values of O_3, CO, NOx, SO_2, and Isoprene would not fall into ranges only within which the Metamodel works appropriately. The other meteorological conditions, rainfall and wind speeds, would not cause such a clear inappropriateness, though they might not give better predictions. Although the following analyses include the results for ANZ, no further interpretations are made to highlight their results, and rather, further work is necessary to rectify the aforementioned inconsistencies of the input variables.

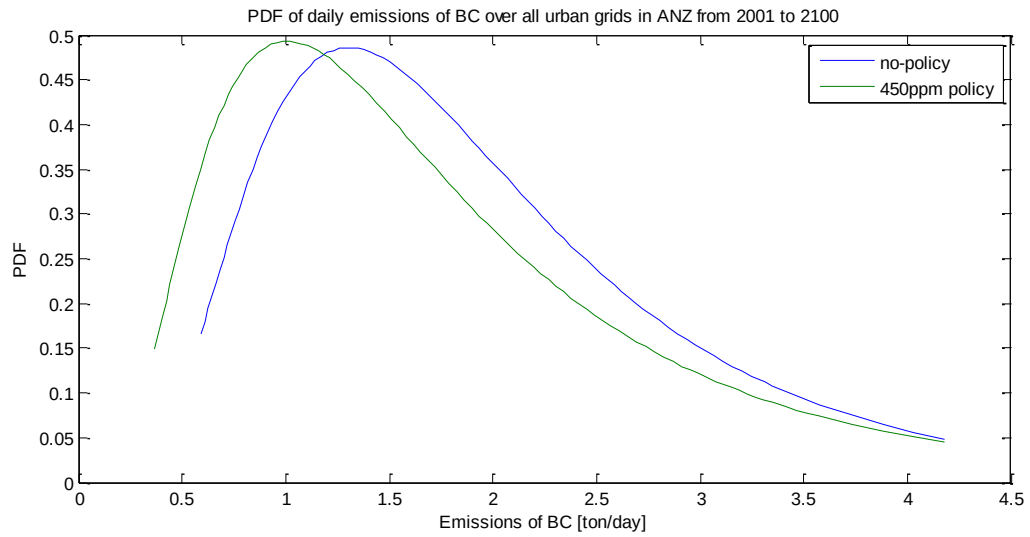


Figure 14 The probability density function of daily emissions of BC over each city in ANZ
(Note: the lines represent the best lognormal fits of the values of daily emissions of BC in each city in ANZ.)

4.4.2. Results by Species

This section analyzes how the features of urban air pollution changes at the global scale in response to the no-policy and 450ppm policy scenarios of the IGSM. In the analyses that follow, each of the key gas species is considered separately and a comparison between the no-policy and policy responses of their concentration is highlighted.

(1) Tropospheric Ozone

Figure 15(a) shows the monthly zonal mean O_3 concentrations for the no policy case. We can see that the O_3 concentrations are increasing as time advances. Tropospheric ozone is not a primarily emitted air pollutant but a secondary one. As described in Section 2.1.3., hydrocarbons such as CO and VOC with NOx contribute to producing tropospheric O_3 and

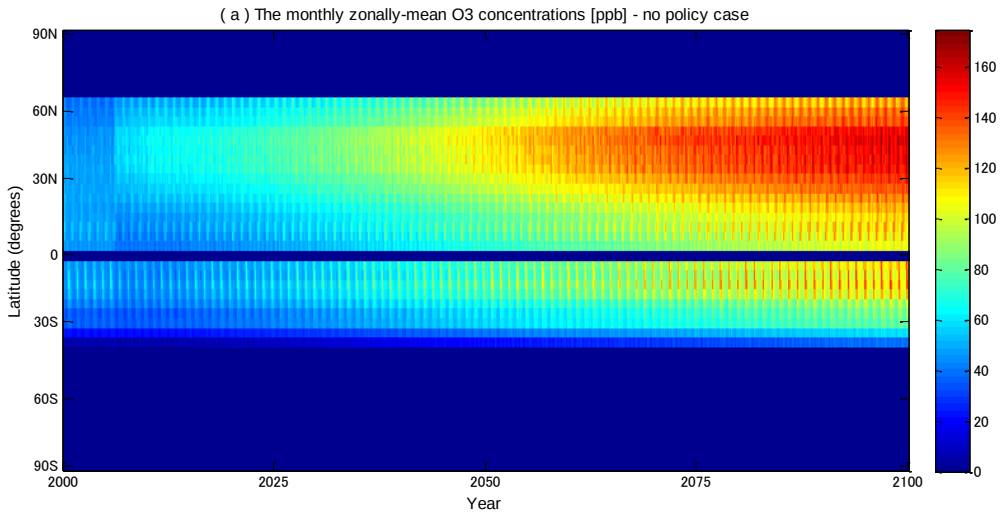
since the emissions of CO, VOC, and NOx are increasing as shown in Figure 13, O_3 also increases. In addition, we observe regular cycle of increase and decrease in the concentrations. This would be due to seasonal variation of the production of tropospheric ozone. In summer, the production of tropospheric O_3 increases due to more active photochemical reactions, whereas the production in winter decreases due to more inactive photochemical reactions. In Figure 15(a), we don't see O_3 around the latitude of 0 degree at all. This is because no city exists there (see Figure 12) and the similar phenomenon in the following figures will be also due to the same reason.

Figure 15(b) shows differences in the monthly zonally-mean O_3 concentrations after imposing the 450ppm policy from the no-policy case. From the figure, we can observe that the differences slightly change roughly from 2050, though they become positive or negative, alternately.

Figure 16 was created by 1) taking a global average of the differences in the monthly zonally-mean O_3 concentrations, the values as shown in Figure 15(b), every month within the latitudes where a city exists; 2) taking a global average of the monthly zonally-mean O_3 concentrations, the values as shown in Figure 15(a), every month within the same latitudinal range; 3) dividing the outputs from 1) by those from 2); and 4) multiply by 100%. From

Figure 16, we can see that the distribution of the monthly global mean changes in the O_3 concentrations over cities and the mean value for the 21th century is approximately 0.123%. These results imply that there is no apparent influence of the 450ppm policy on the O_3 concentrations at the global scale.

As described later in Figure 19(b), the concentrations of NO_2 decrease with policy. Also, since it is a primary pollutant, VOC emissions reductions by policy could decrease its concentrations in the air. However, since VOC and NOx generally compete for OH radicals, the reduced VOC does not necessarily mean the reduction of O_3 and in turn, the reduced NOx does not necessarily imply the reduction of O_3. Rather, the efficiency in producing O_3 depends on the ratio of the concentrations of NOx to those of VOC, which could also depend on meteorological and geographical conditions for each calculation.



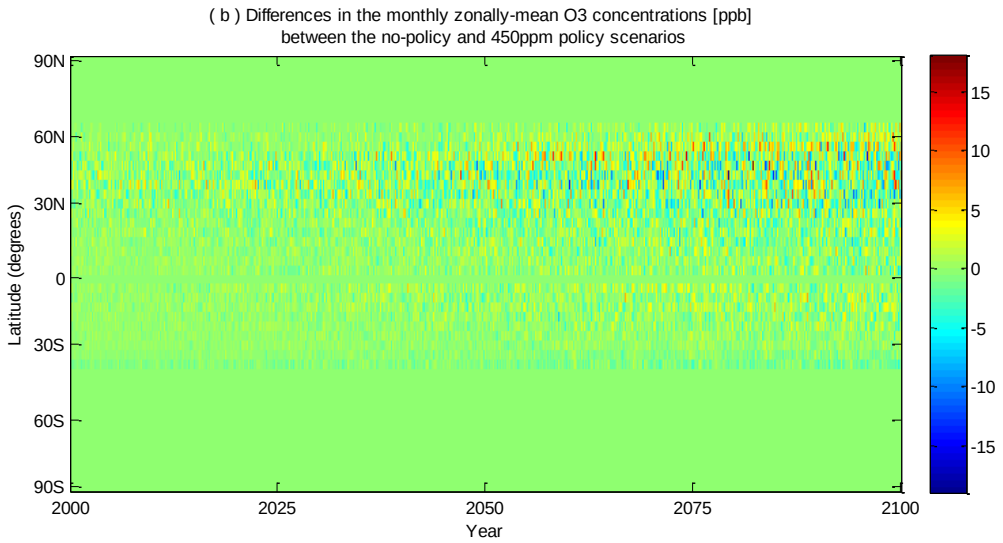


Figure 15. (a) The monthly zonally-mean O_3 concentrations [ppb] in urban areas and (b) the differences in the monthly zonally-mean O_3 concentrations [ppb] between the no-policy and 450ppm policy cases

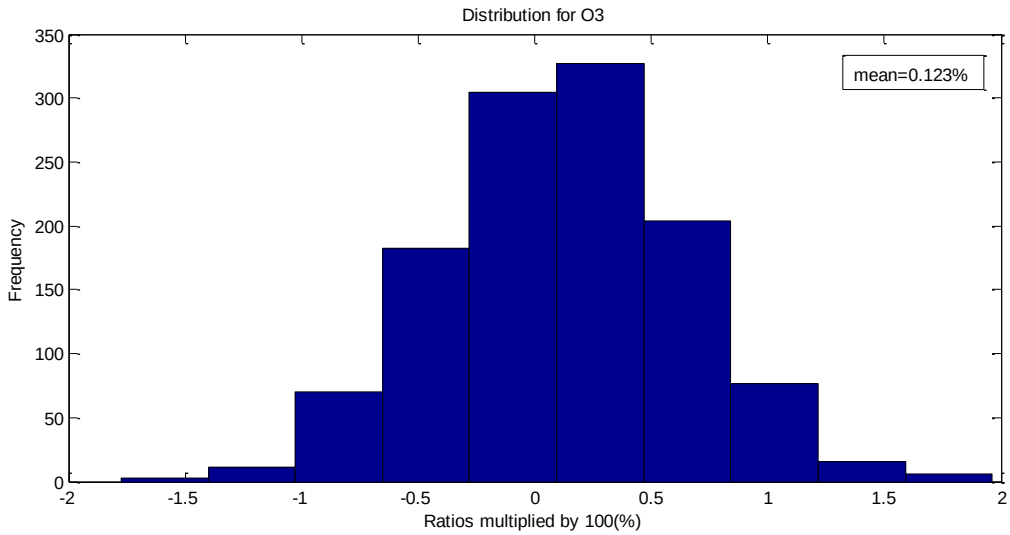
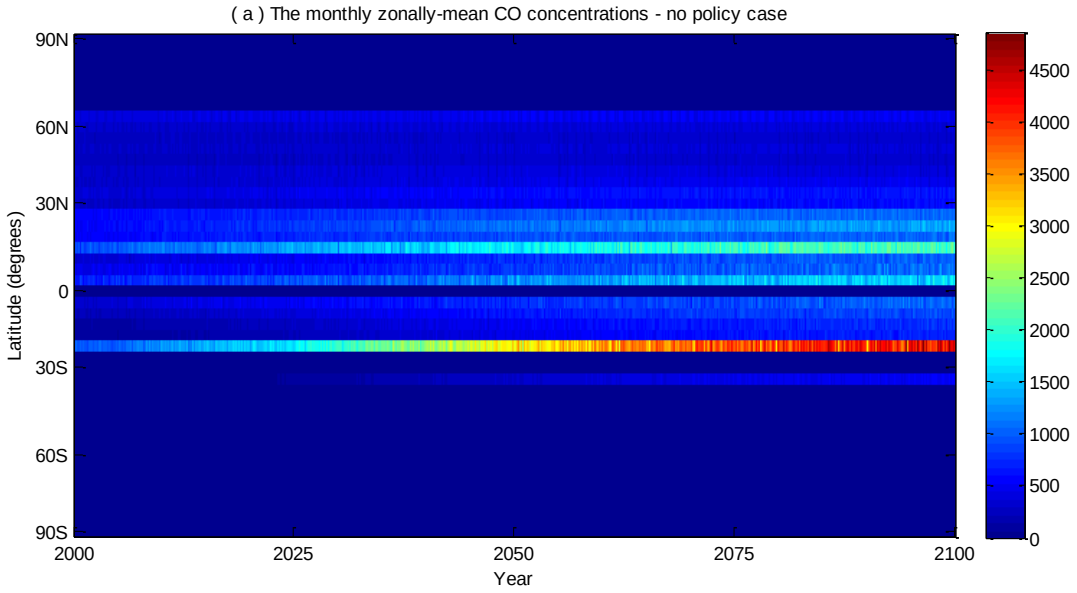


Figure 16. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean O_3 concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean O_3 concentrations for the no-policy case multiplied by 100%

(2) Carbon Monoxide

From Figure 17(a), we can see that the concentrations of CO slightly increase all areas where cities exist for the whole 21th century, approximately from less than 1ppm up to 4.5ppm without the climate policy. From Figure 17(b), we observe that the 450ppm policy slightly

decreases the CO concentrations and Figure 18 also demonstrates that the impact of the policy is approximately by -3.84% at the global scale. This would be mainly due to the reduction of emissions of CO under the policy, because CO is a primary air pollutant. Another reaction path could be the reaction of CO with OH, though the concentrations of OH are unavailable in the offline version of the Metamodel. To examine to what degree this path could contribute to the reduction of CO concentrations, we need to examine the concentrations of OH.



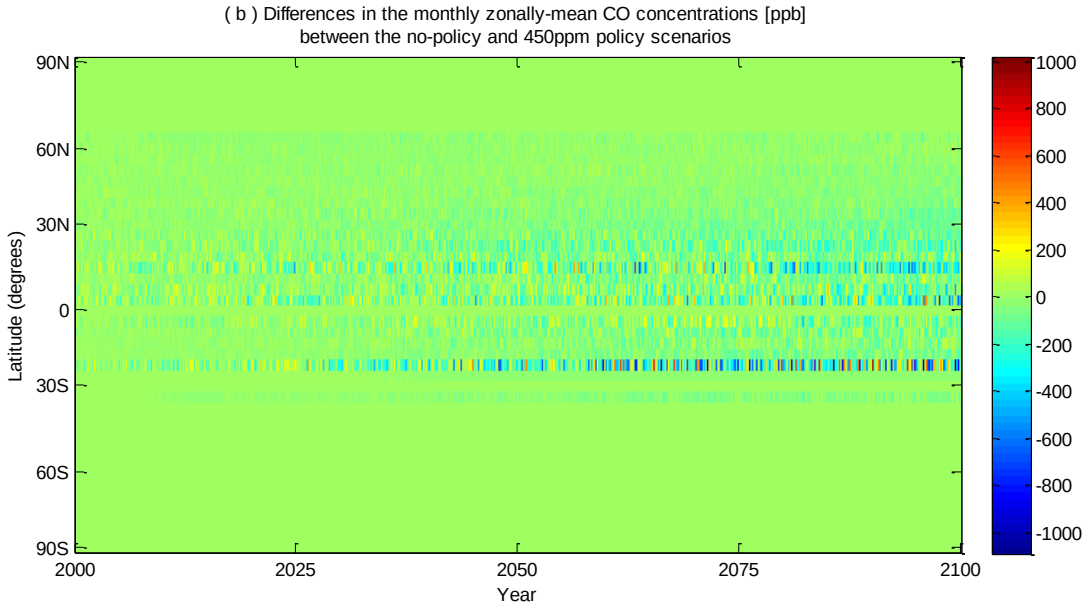


Figure 17. (a) The monthly zonally-mean CO concentrations [ppb] in urban areas and (b) the differences in the monthly zonally-mean CO concentrations [ppb] between the no-policy and 450ppm policy cases

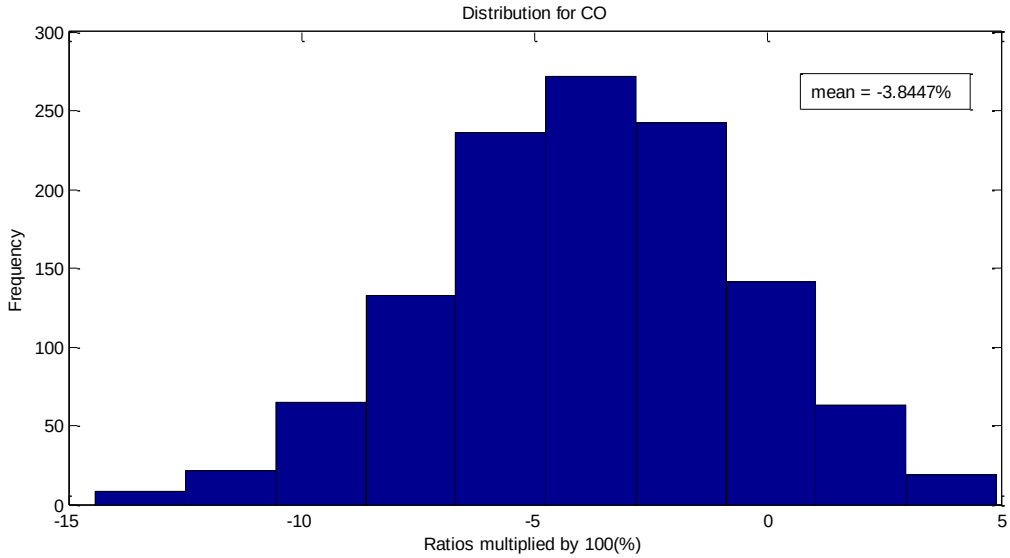


Figure 18. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean CO concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean CO concentrations for the no-policy case multiplied by 100%

(3) Nitrogen Dioxide

Figure 19(a) shows that the mole fractions of NO_2 for no policy case increase in the long term.

However, we can see higher concentrations around latitude of 19.5^{o}S and slightly around

latitudes from 9.5°N to 24.5°N. Since NOx including NO_2 is a primary air pollutant emitted through industrial activities, this would result from high emissions of NOx. However, even though we also see high concentrations in latitudes between 29.5°N to 49.5°N, we observe lower concentrations in the latitudinal range. Although theoretically, NO_2 is transported over long distances by subtropical jet stream, the new Metamodel does neither consider transboundary effect nor accumulation over 1 day. Instead, the zonal variability would result from differences in meteorological conditions. In this regard, we will need further work.

From Figure 19(b), we can observe that differences of the monthly mean concentrations after imposing the policy increase as time advances, indicating the 450ppm policy would decrease the NO_2 concentrations. Since NO_2 is a primary pollutant, the reduction of NO_2 emissions as shown in Figure 13(c) can reduce the concentrations of NO_2 in the air. However, NOx normally consists of 95% of NO and 5% of NO_2 in the air, the reduction of emissions of NOx would not have substantial influence. NO_2 can be also a secondary product of the reaction of NO to hydroperoxyl or peroxy radicals (HO_2, RO_2). Therefore, the reduction of emissions of NO as well as the reduction of emissions of CO and VOC by the policy could explain the reduced concentrations of NO_2. However, as shown in Figure 13(a) and Figure 13(b), the degrees of the reduction of emissions of CO and VOC by the policy are not substantial; 9.7% and 6% respectively at least at the global scale in 2100. Therefore, even though the reduction of emissions of NO is large, 27% at the global scale in 2100, this may turn out to have a small

impact on the reduction of the concentrations of NO_2. In fact, from Figure 20, we see that the 450ppm policy would decrease NO_2 approximately only by -4.42% at the global scale.

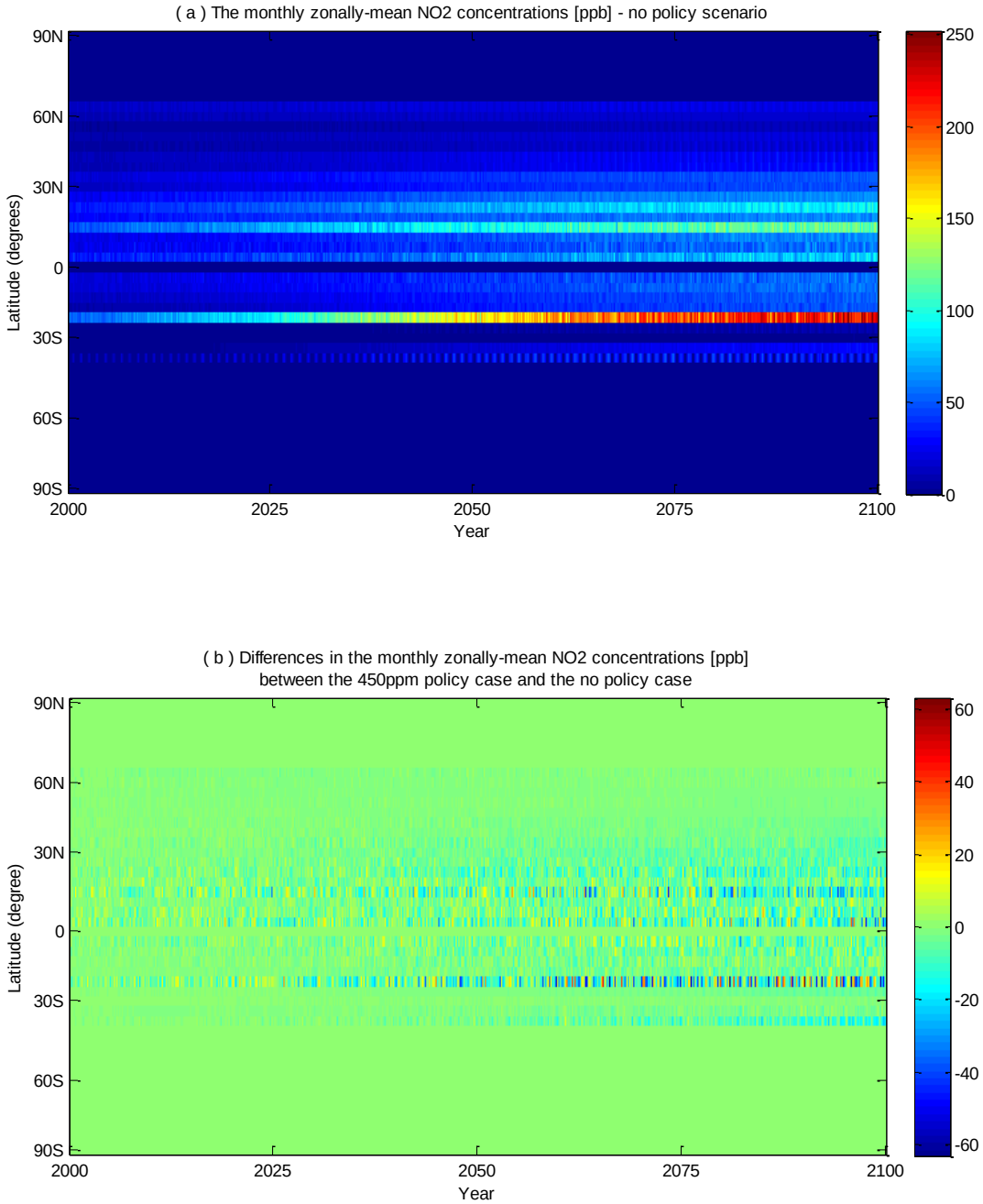


Figure 19. (a) The monthly zonally-mean NO_2 concentrations [ppb] in urban areas and (b) the differences in the monthly zonally-mean NO_2 concentrations [ppb] between the no-policy and 450ppm policy cases

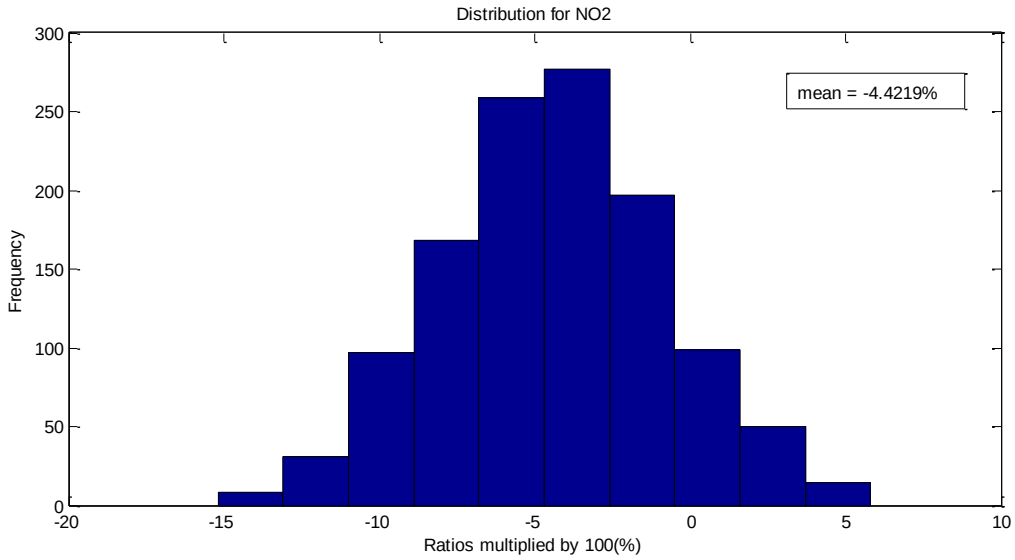


Figure 20. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean NO_2 concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean NO_2 concentrations for the no-policy case multiplied by 100%

(4) Sulfur Dioxide

Figure 21(a) shows that the mole fractions of SO_2 over cities range from 0 to 25ppb for the no-policy case. The highest concentrations around the latitudes between 35.5°S to 38.5°S are the results for cities in Australia or New Zealand. As mentioned before, since SO_2 cannot be predicted well by the Metamodel for the region, we should exclude them.

The same is applied for the highest values around the latitudes in Figure 21(b). However, we can see that declines in the concentrations in latitudes from 29.5°N to 59.5°N, where most of the cities exist. It can be also explained from Figure 22, which demonstrates that the 450ppm policy reduces SO_2 for the whole period on average by -79.0% from the no policy case, though the averaged reduction may be overestimated due to the inclusion of the results for

Australia and New Zealand. The reduction of the SO_2 concentrations would be primarily due to the decrease in the SO_2 emissions as SO_2 is a primary pollutant, not a secondary product.

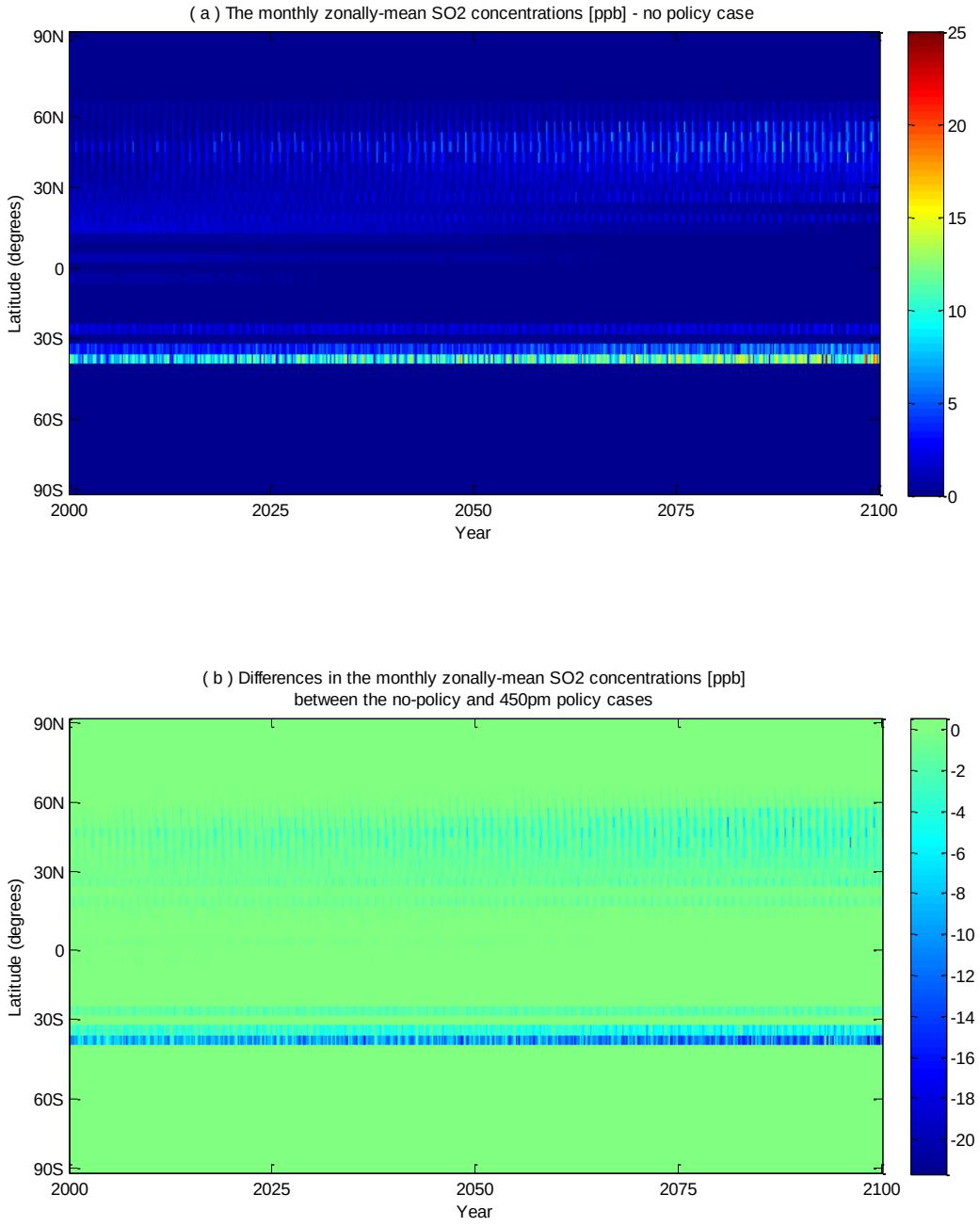


Figure 21. (a) The monthly zonally-mean SO_2 concentrations [ppb] in urban areas and (b) the differences in the monthly zonally-mean SO_2 concentrations [ppb] between the no-policy and 450ppm policy cases

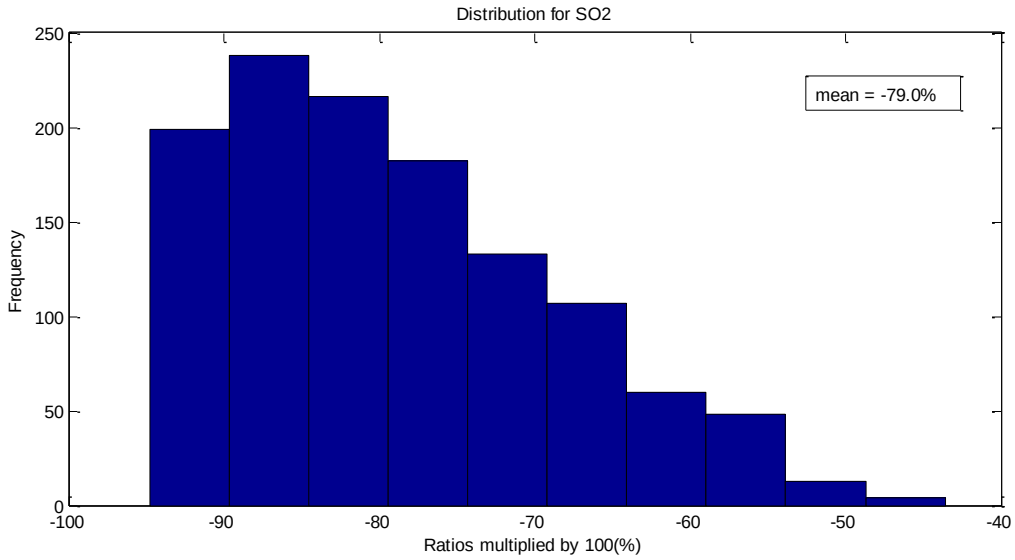


Figure 22. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean SO_2 concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean SO_2 concentrations for the no-policy case multiplied by 100%

(5) Formaldehyde

In Figure 23(a), we can see that the mole fractions of HCHO range from 0 to 50ppb over cities, increasing over time. Basically, HCHO is a primary pollutant emitted from industrial activities and it can be also produced through the photochemical reactions of non-methane hydrocarbons including CO and VOC. Since the Metamodel does not include HCHO as a primary emission source, we conclude that the second path would result in Figure 21(a). In fact, Figure 21(a) resembles Figure 17(a): more HCHO can be found where more CO is found. Figure 23(b) shows the differences of the monthly mean concentrations after implementing the climate policy. It shows decreases in the concentrations evenly across latitudes where cities exist. The reduction of the concentrations can be also explained by

Figure 24, from which we conclude that the globally averaged reduction is -6.52%. Similar to the case for CO, the climate policy reduces emissions of CO and VOC as shown in Figure 13(a) and (b), resulting in the reduced production of HCHO.

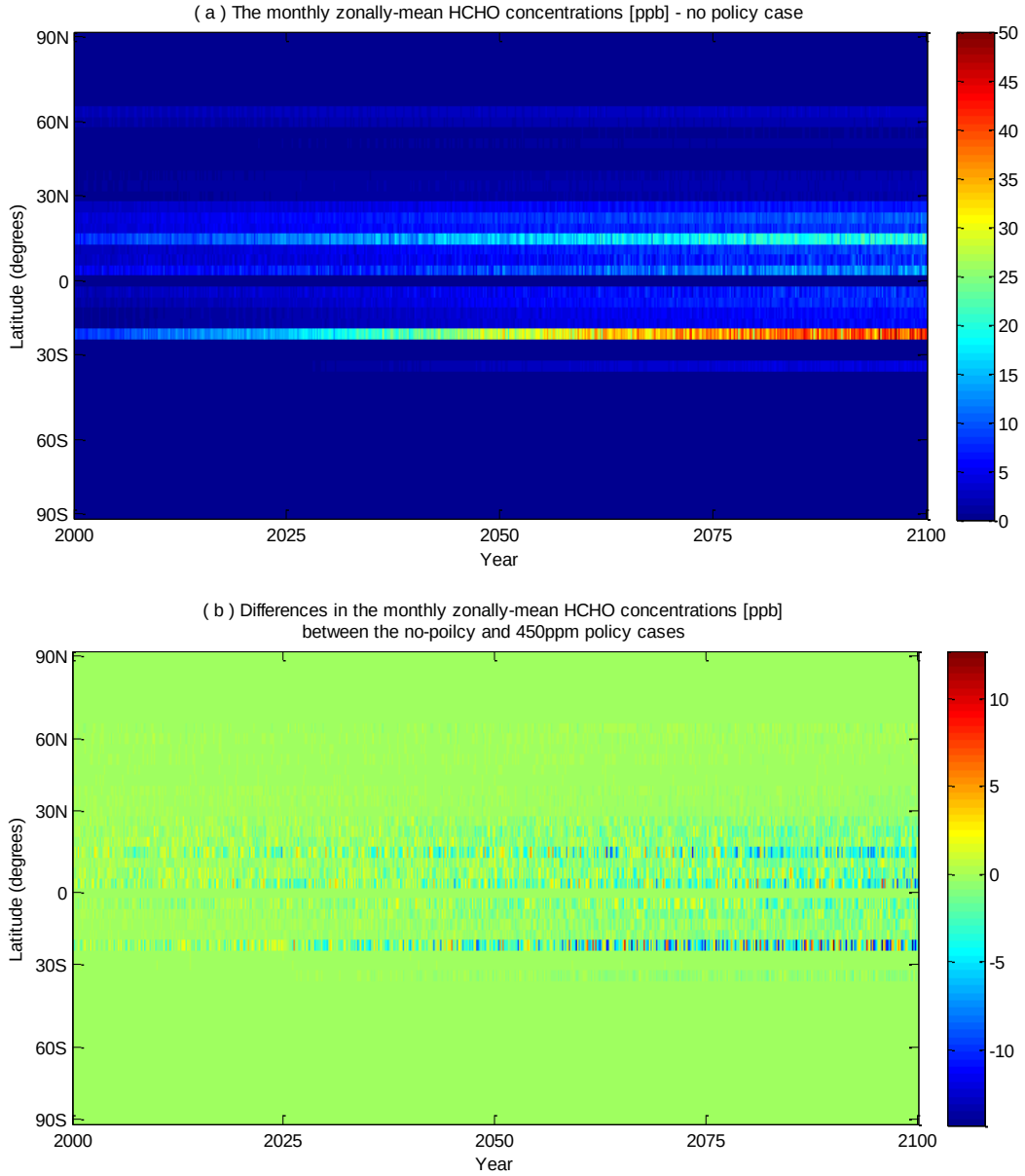


Figure 23. (a) The monthly zonally-mean HCHO concentrations [ppb] in urban areas and (b) the differences in the monthly zonally-mean HCHO concentrations [ppb] between the no-policy and 450ppm policy cases

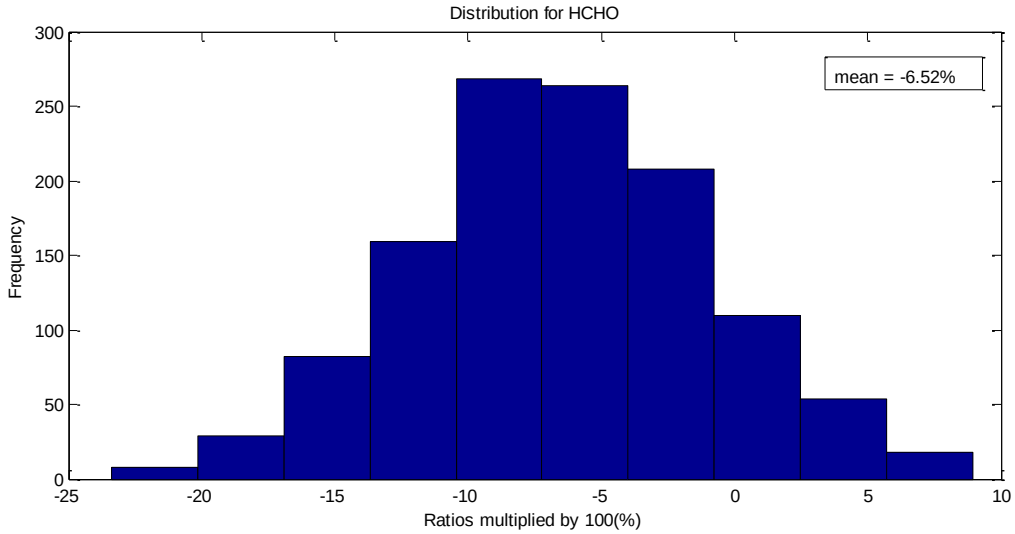


Figure 24. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean HCHO concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean HCHO concentrations for the no-policy case multiplied by 100%

(6) Sulfate aerosols

From Figure 25(a), we observe that sulfate aerosols mainly in latitudes from 29.5^{o}N to 59.5^{o}N and the order is approximately 1x10^{9} [ug/m^{3}]. Overall, the values neither increase nor decrease for the 21th century. In addition, we estimate that emissions of SO_2 decrease even without a climate policy as shown in Figure 13. They imply that the degrees of emissions of SO_2 would not determinately influence the concentrations of sulfate aerosols, even though SO_2 is a major source of H_2SO_4. Rather, other natural conditions associated with the formation of sulfate aerosols would result in relatively constant production of sulfate aerosols for the whole period.

In addition, while we see some negative values, the Metamodel does not expect a value of

concentration to be negative. This would be due to inappropriate inputs for some cities or due to limitation of the Metamodel for calculating sulfur-containing species (Cohen & Prinn, 2009).

From Figure 25(b), we do not see clear differences of the concentrations after imposing the policy. This can be also explained by the assumptions as described above that the concentrations would be primarily determined not by emissions but by other natural processes and if we assume that natural processes would not change substantially even with the climate policy, we can assume that the differences of the concentrations after the policy would not be clear.

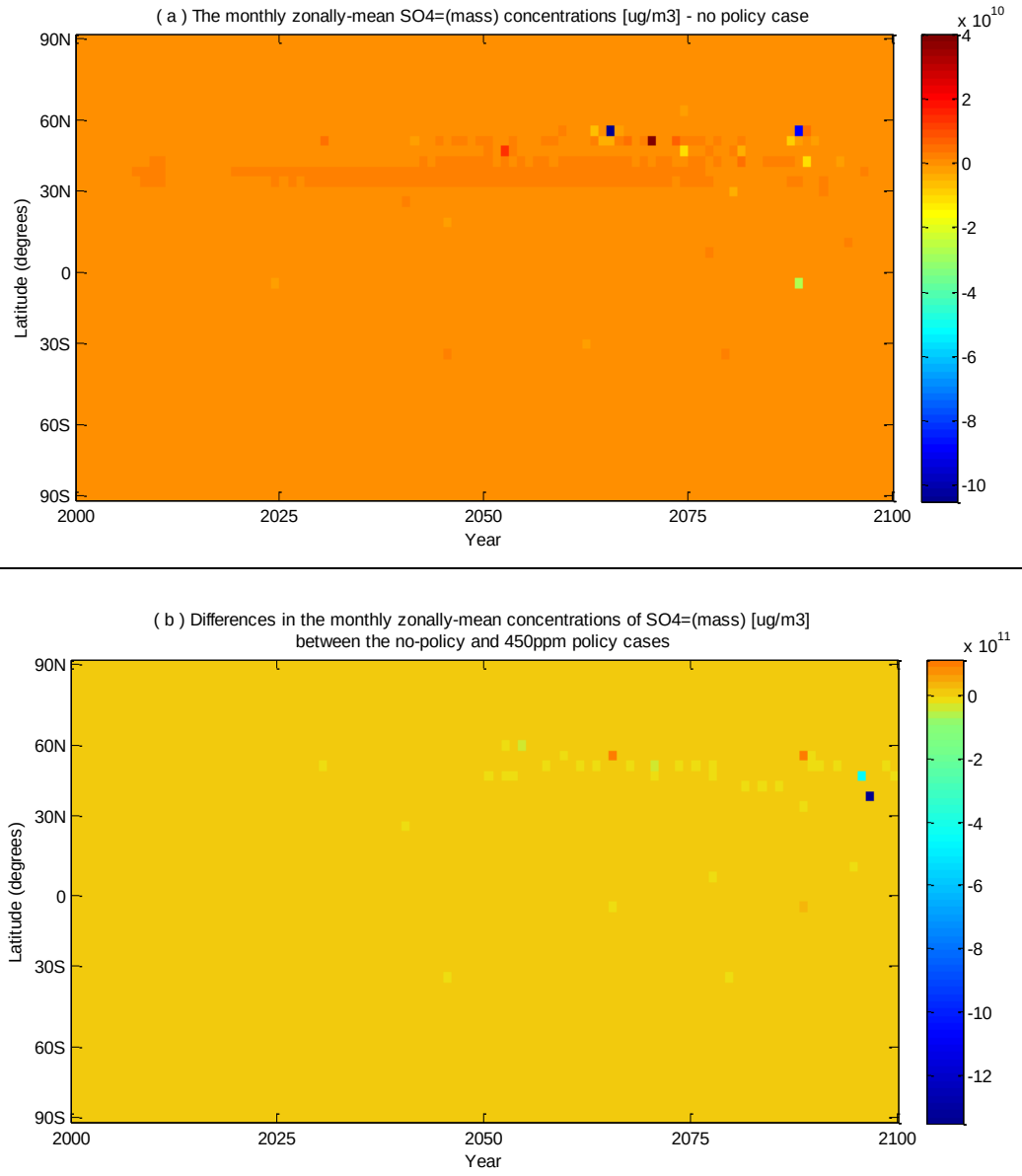


Figure 25. (a) The monthly zonally-mean concentrations of sulfate aerosols [ug/m^3] in urban areas and (b) the differences in the monthly zonally-mean concentrations of sulfate aerosols [ug/m^3] between the no-policy and 450ppm policy cases

(7) Black carbon

From Figure 26(a), we observe that black carbon is distributed across latitudes where

cities exist, focusing on those between 29.5^{o}N to 59.5^{o}N. The emission sources vary, depending on region, and in developed countries in the northern hemisphere, a primary source is fuel combustion. The global averaged concentration over cities from 2001 to 2100 is approximately 3x10^{5} [ug/m^{3}], slightly decreasing for the period even without climate policy, mainly because emissions of BC decrease even for the no-policy case. Although a few negative values are observed, they would be because inputs for the Metamodel were not appropriate.

Figure 26(b) shows the differences of the concentrations after imposing the policy. It does not necessarily show increase in differences, though the impact of the policy is in both positive and negative directions.

Figure 27 shows that with the 450ppm policy, the concentration would be reduced on average by -15.3% from the no-policy case.

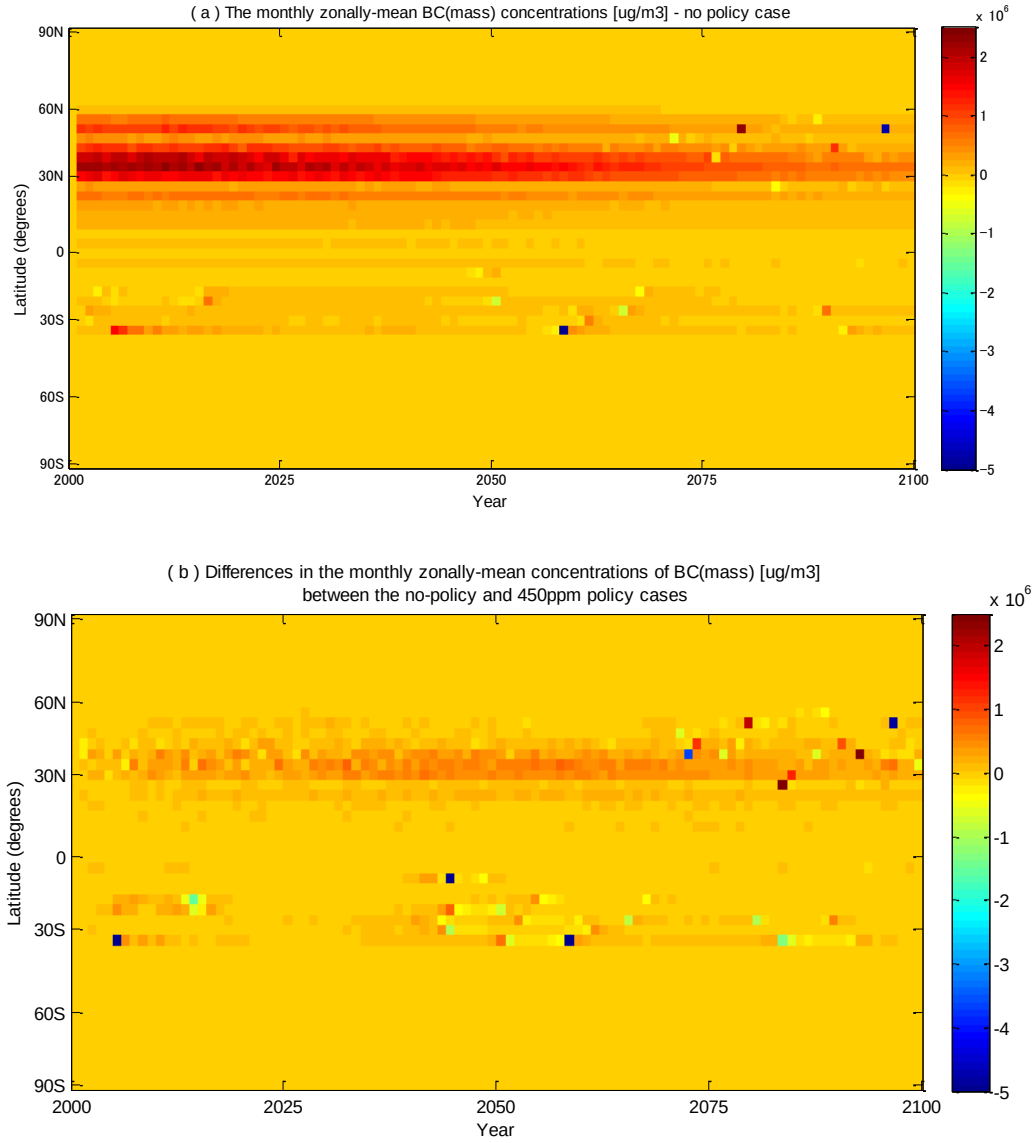


Figure 26. (a) The monthly zonally-mean BC(mass) concentrations [ug/m^3] in urban areas and (b) the differences in the monthly zonally-mean BC(mass) concentrations [ug/m^3] between the no-policy and 450ppm policy cases

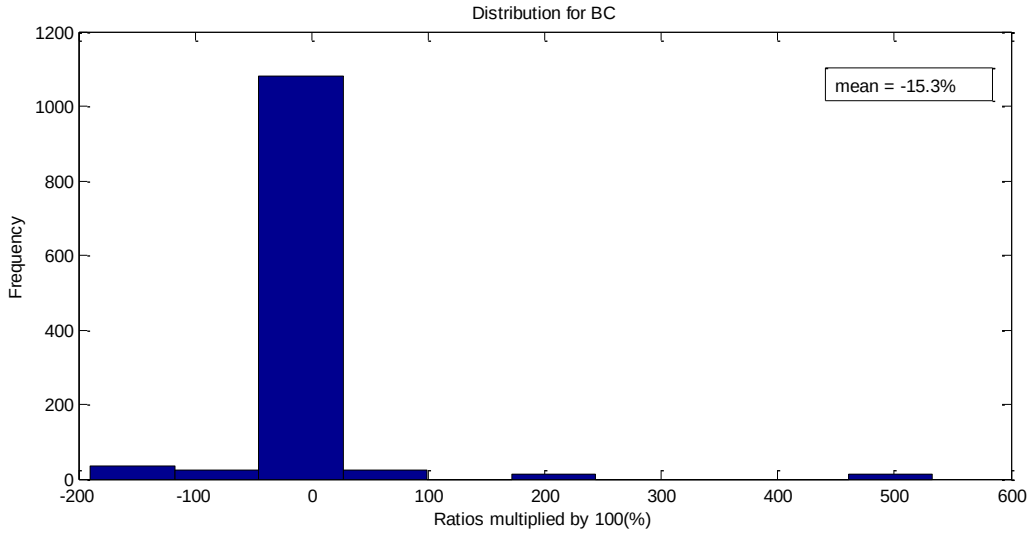


Figure 27. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean BC(mass) concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean BC(mass) concentrations for the no-policy case multiplied by 100%

(8) Organic Carbon

Similar to BC, from Figure 28(a), we observe that OC in latitudes between 19.5^{o}N to 59.5^{o}N, slightly decreasing for the 21th century, and that the global averaged concentration over cities from 2001 to 2100 is approximately 4x10^{5} [ug/m^{3}]. However, we cannot see a clear tend in differences of the concentrations after imposing the policy at least at the global scale as demonstrated in Figure 28(b). The more detailed study at the regional scale in the next section will reveal clearer trends. Furthermore, while Figure 29 tells the mean ratio of the differences to the mean concentrations is -27.8%, the ratio may be affected by salient values.

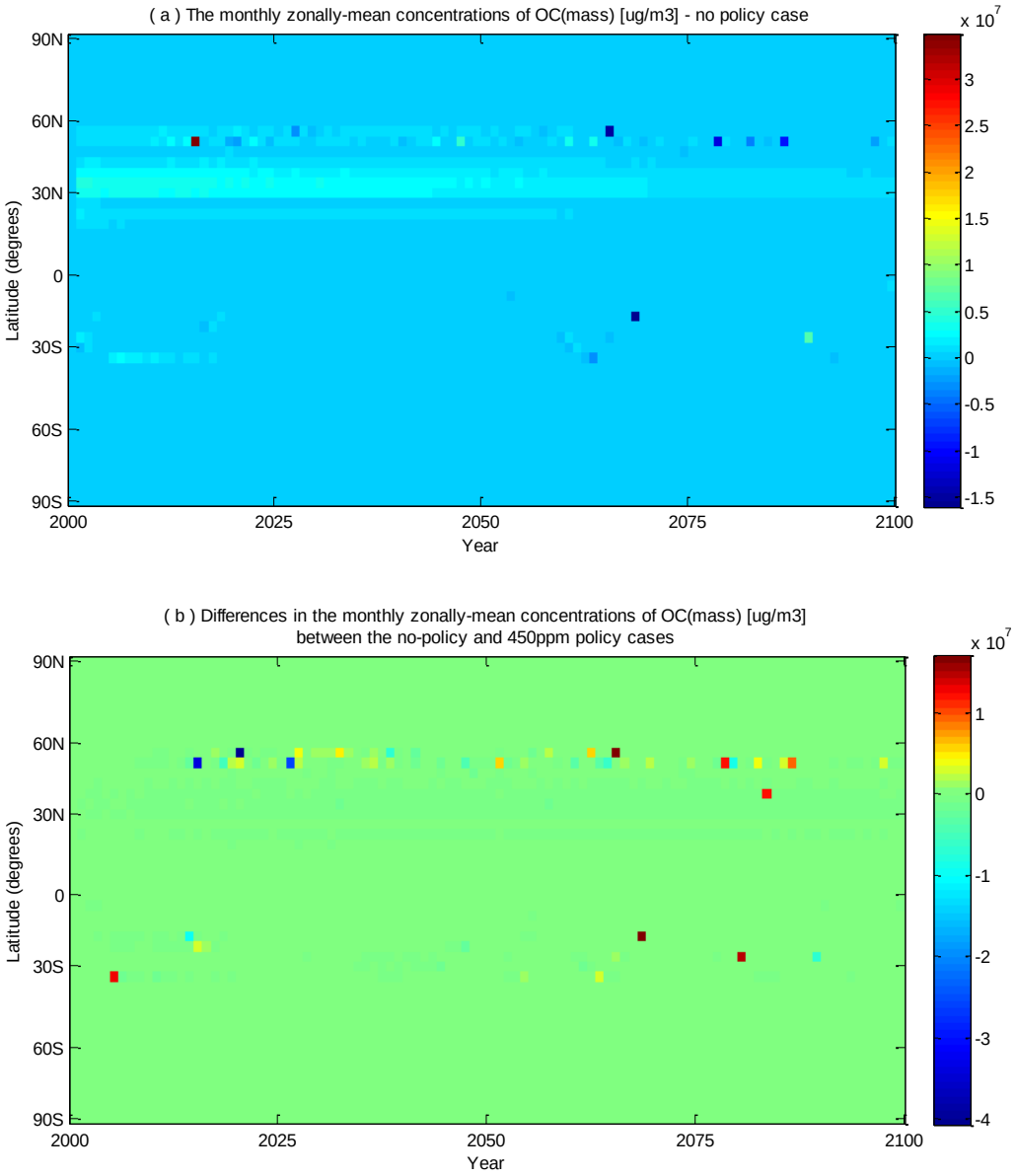


Figure 28. (a) The monthly zonally-mean OC(mass) concentrations [ug/m^3] in urban areas and (b) the differences in the monthly zonally-mean OC(mass) concentrations [ug/m^3] between the no-policy and 450ppm policy cases

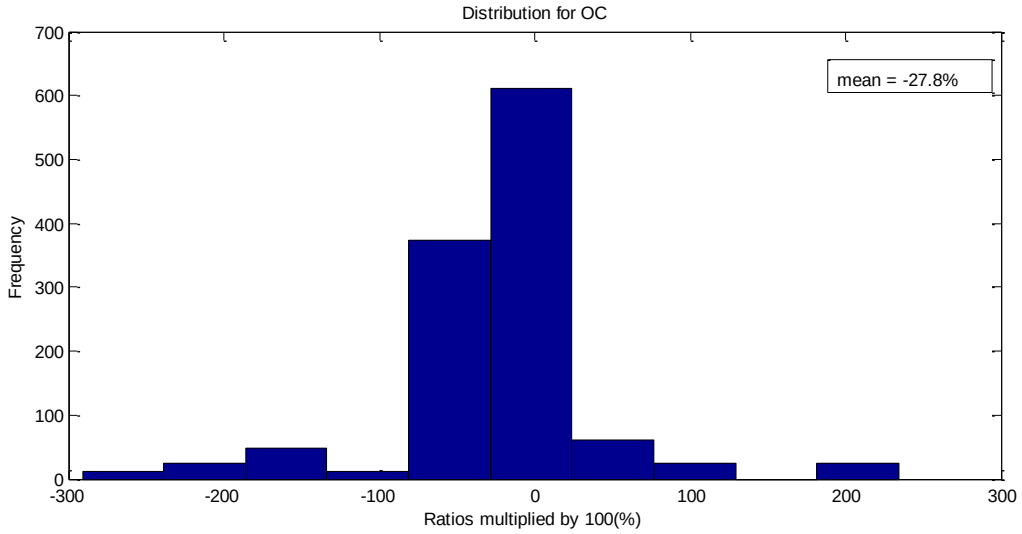


Figure 29. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean OC(mass) concentrations between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean OC(mass) concentrations for the no-policy case multiplied by 100%

(9) Nitrate aerosols

In Figure 30(a), clear observation of nitrate aerosols in the southern hemisphere is probably due to the inappropriate estimates for Australia and New Zealand as mentioned in Section 4.4.1. On the other hand, we can observe very few nitrate aerosols in the northern hemisphere. Since nitrate aerosols are primarily formed by the reaction of HNO_3 to NH_3, the following would result: 1) the very little amount of NH_3; 2) the very small amount of OH radicals for the reaction to NOx to form HNO_3 due to other reaction paths such as consumption of OH by hydrocarbons; or 3) other reasons. As shown in Figure 32, NH_3 is emitted much more in the northern hemisphere, though we may see a different trend in its concentrations. If we assume the trend in the NH_3 concentrations is similar to that in NH_3 emissions, the first assumption will be unrealistic. The second assumption may be possible, because the reaction is well

known as one of the key reactions that convert NOx into its reservoir, HNO_3 and, in fact, its rate constant is not slow, in the order of 10^{-12} [$cm^{-3}s^{-1}$]. Furthermore, the unclear observation of nitrate aerosols in the northern hemisphere in spite of the fact that NOx is substantially emitted would also result from chemical and physical characteristics of nitrate aerosols, i.e., highly soluble, easily deposited to land and material surfaces, of which reaction mechanism is not straightforward.

Also, Figure 30(b) shows that differences of the concentrations of nitrate aerosols are both positive and negative and, from Figure 31, we do not clearly see that the policy would affect nitrate aerosols at least at the global scale.

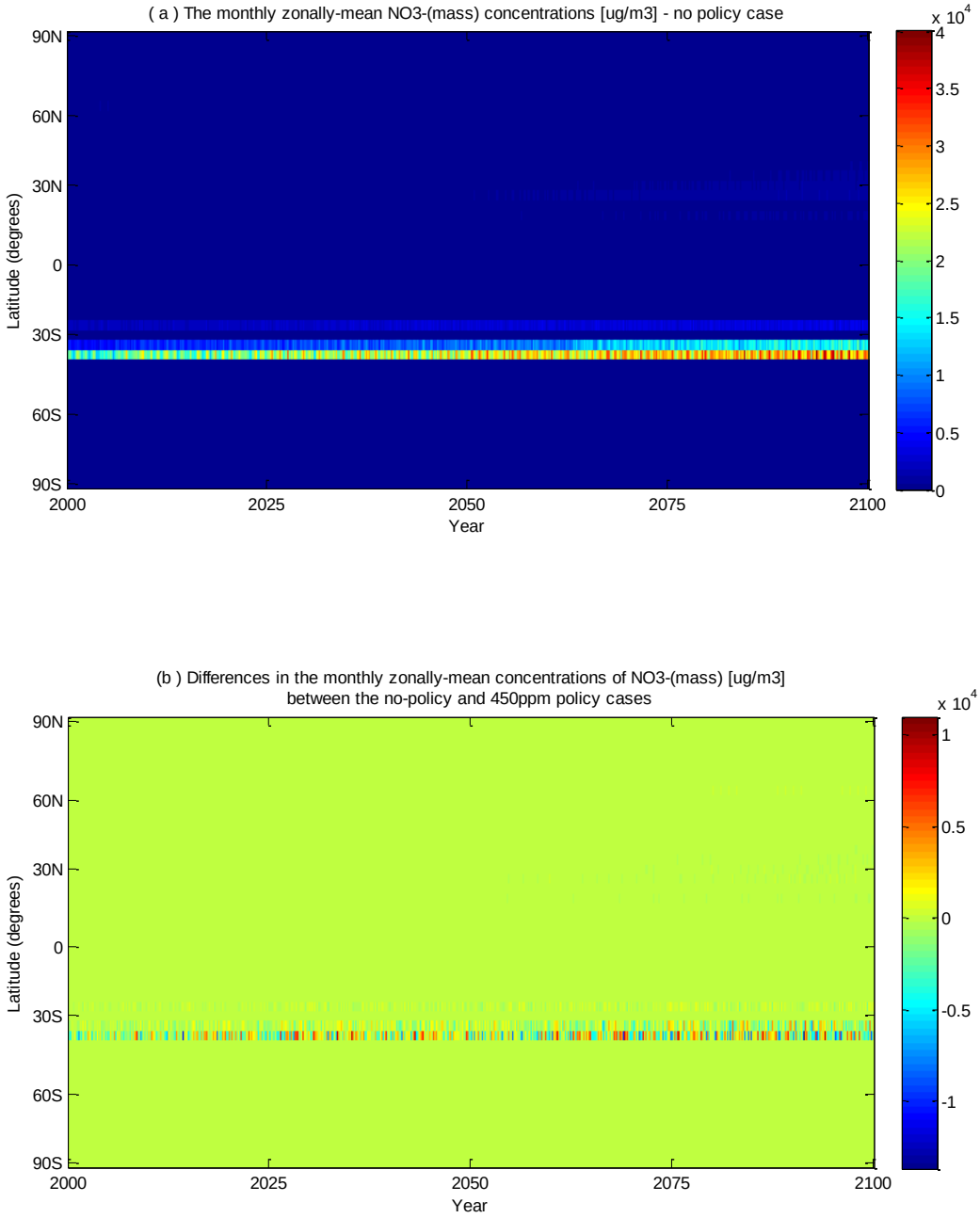


Figure 30. (a) The monthly zonally-mean concentrations of nitrate aerosols (mass) [ug/m^3] in urban areas and (b) the differences in the monthly zonally-mean concentrations of nitrate aerosols (mass) [ug/m^3] between the no-policy and 450ppm policy cases

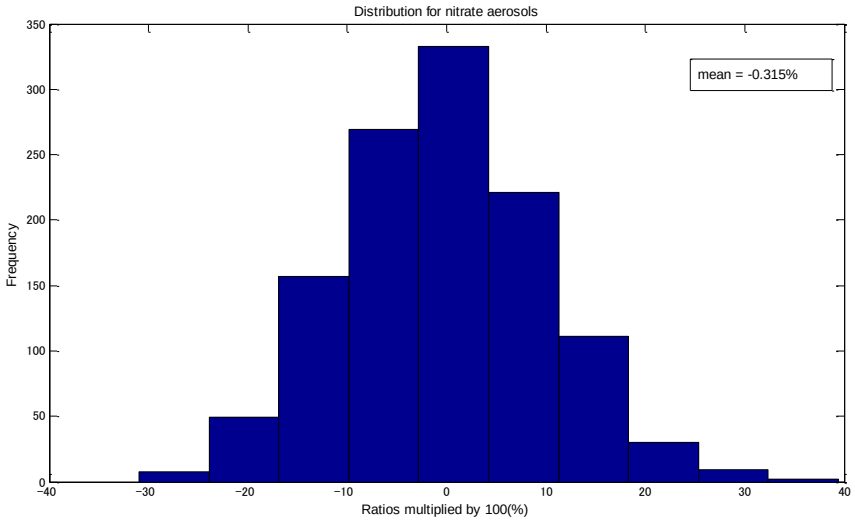


Figure 31. The distribution of the ratios of the difference in the globally averaged monthly zonally-mean concentrations of nitrate aerosols (mass) between the no-policy and 450ppm policy cases to the globally averaged monthly zonally-mean concentrations of nitrate aerosols (mass) for the no-policy case multiplied by 100%

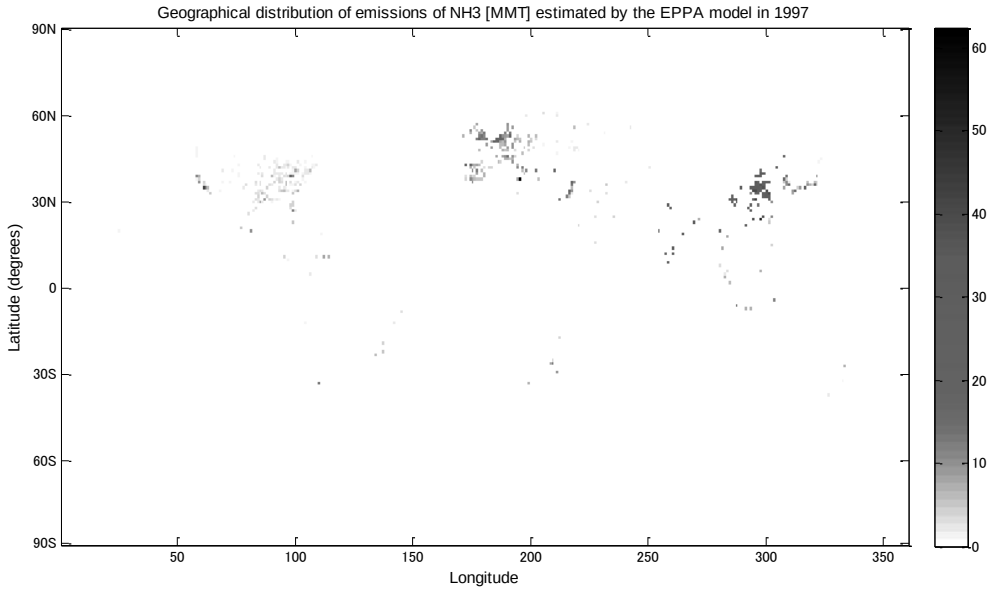


Figure 32. The geographical distribution of emissions of NH_3 [MMT] in 1997 estimated by the EPPA model

4.4.2. Summary

Since most of the urban grids exist in the northern hemisphere, the majority of anthropogenic

emissions are also produced from the hemisphere. Therefore, with regard to the figures for the no-policy case, it is not surprising that the majority of pollutants are found in the northern hemisphere.

In the next section, we will see the geographical variability of the concentrations not only from the two sides of the sphere but also from a more detailed regional viewpoint. In terms of the policy-impacts, although the global-scale impacts of the 450ppm policy would widely vary by species, it can be concluded that:

1) the 450ppm policy would neither affect the concentrations of O_3, sulfate aerosols, nor nitrate aerosols;
2) CO, NO_2, HCHO, BC, OC, and nitrate aerosols can be either increased or reduced, and the magnitudes would vary; however,
3) SO_2 is likely to be reduced, approximately by -79% for the 21^{th} century, though the reduction rate would be uncertain due to the inappropriate estimates for Australia and New Zealand.

4.5. Regional and Temporal Variability in the Impacts of the 450ppm Policy on Urban Air Pollution

4.5.1. Results by Species

One of the most important features of the new Metamodel is to enable simulations by 1-by-1-degree, though the previous version of the urban airshed model provides only zonal outputs. Coupled with the IGSM, this 1-by-1-degree analysis allows us to make comparisons among regions, each of which represents a variety of city types according to their urban airshed environment.

The following figures, from Figure 33 to Figure 49, describe the changes in the monthly mean concentrations of the key air pollutants averaged over all 1-by-1-degree urban grids in each EPPA region for the different three periods; (1) from 2001 through 2020; (2) from 2001 through 2050; and (3) from 2001 through 2100. In all figures, each mean value is calculated by (1) finding the monthly mean concentration averaged across each EPPA region for the no policy case (a) and policy case (b) respectively; (2) taking the differences between the two cases (b-a); and (3) dividing the difference of the monthly mean concentrations by the monthly mean concentration for the no policy case ([b-a]/a) – and then multiply this value by 100%. As such, these figures are designed to illustrate the response of these gas species to a 450 ppm stabilization policy, relative to the no policy conditions. The detailed quantitative

results are shown with the median values and the standard deviations of the mean concentrations for the no policy and the 450ppm policy cases in Appendix A.

(1) Tropospheric Ozone

Figure 33 shows the mean ratio of the differences of the monthly mean concentrations of O_3 after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case, multiplied by 100% for the 3 different periods: 20, 50, and 100 years by region.

The impacts of the 450ppm policy on the O_3 concentrations are less than 5% for any of the three periods (Figure 33), which is consistent with the results for the global-level analysis (see Figure 16).

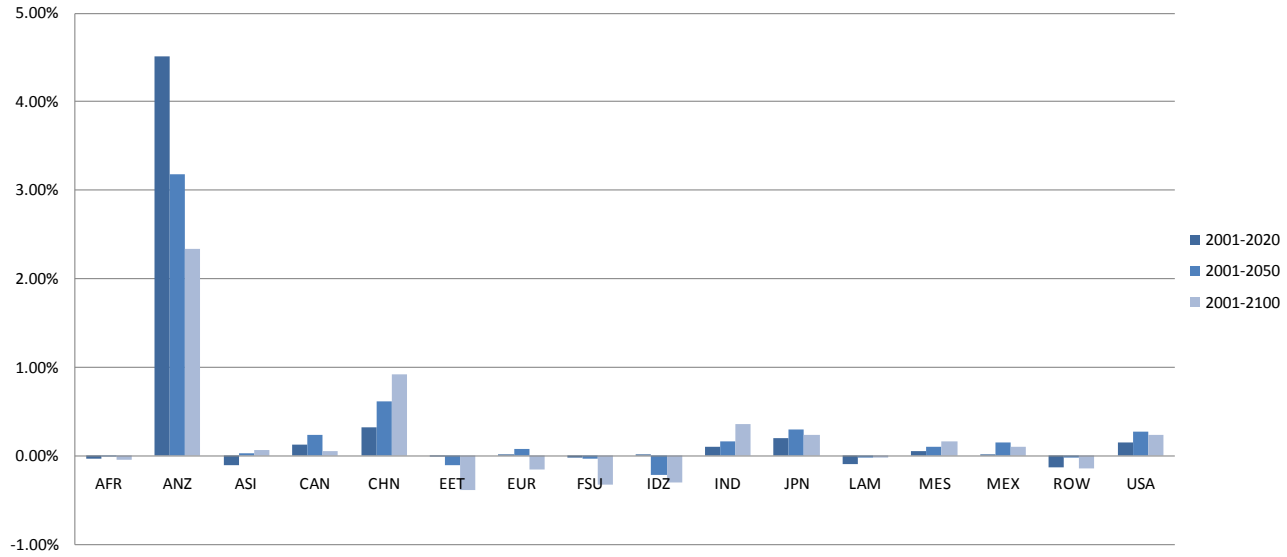


Figure 33. The mean ratio of the differences of the monthly mean concentrations of O_3 after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3

different periods: 20, 50, and 100 years.

(2) Carbon Monoxide

From Figure 34 and Figure 35, regional variability is seen to be relatively small except for Africa and China, where the reductions are more than -10% for the 100-year period and even for the 20-year period, China has the reductions approximately by -4%. In spite of the larger reduction rates, however, the monthly mean concentrations over cities in Africa and China for the no policy case are 31.6ppb and 328ppb for the 20-year period, and they are not higher than those in East Asian countries with higher income levels and Mexico. In East Asia and Mexico, on the other hand, the monthly mean concentrations are 1.07 ppm and 1.14 ppm for the same period (see Appendix A). The larger mean concentrations with the smaller rates of reduction would be caused by increased emissions over the regions for both scenarios, with few removal processes in addition to less effective emissions reductions due to the policy.

On the other hand, in Africa and China, the larger anthropogenic emissions, 0.2~1.0 TgCO/year (EDGAR 32FT2000[18]), with the larger reduction rates and the smaller concentrations indicate that the policy effectively cuts the emissions and that while India, Latin America, and the Middle East also have larger emissions, 0.1~1.0TgCO/year (EDGAR

[18] http://www.rivm.nl/edgar/model/v32ft2000edgar/edgarv32ft-prec/edgv32ft-co-map.jsp

32FT2000[19]), the reductions are smaller, probably because the policy cuts the emissions less effectively and the removal by natural processes might also contribute. Finally, the contributions of the policy to the reductions of CO become larger in the longer term in almost all regions.

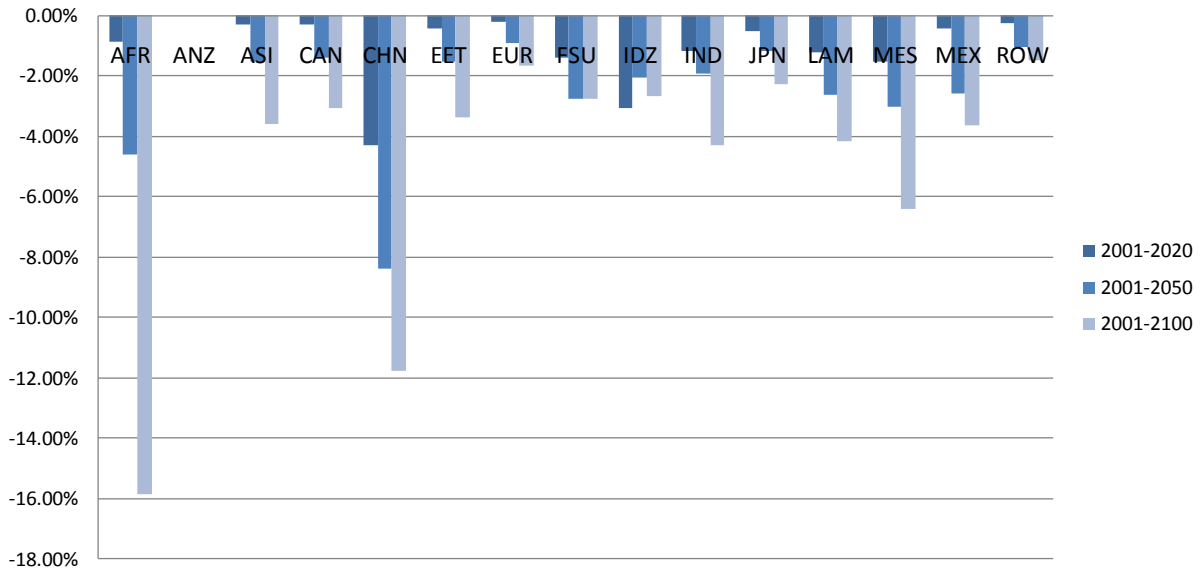


Figure 34. The mean ratio of the differences of the monthly mean concentrations of CO after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years.
(Note: The data for ANZ is absent because its concentrations are not predicted well.)

[19] http://www.rivm.nl/edgar/model/v32ft2000edgar/edgarv32ft-prec/edgv32ft-co-map.jsp

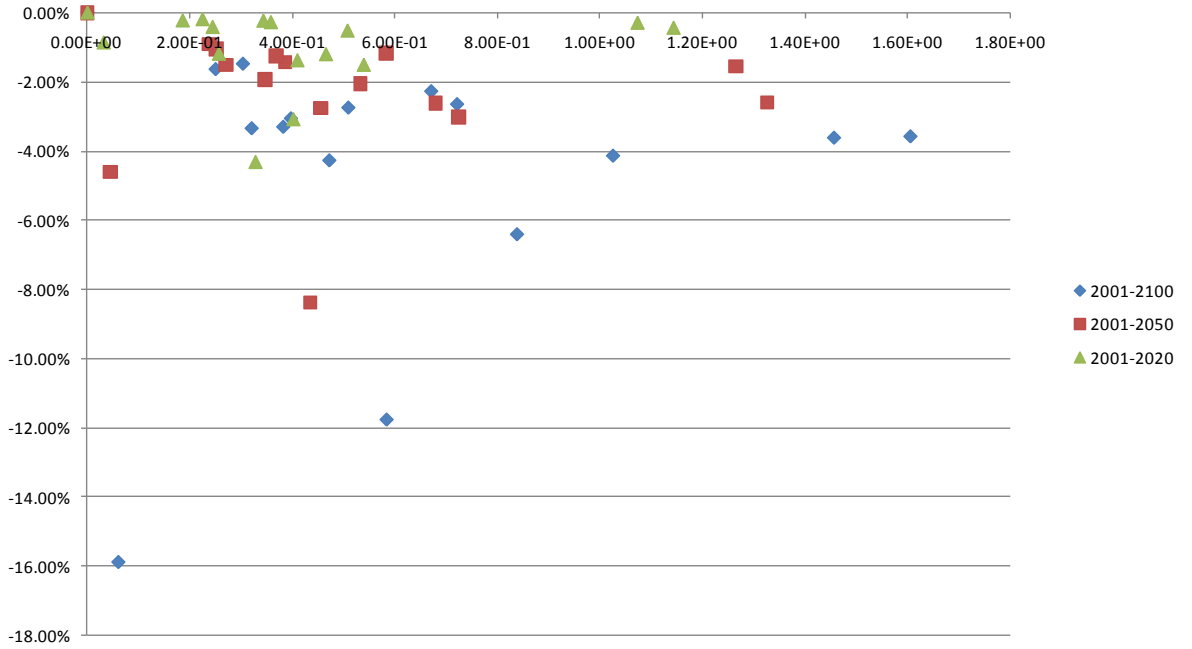


Figure 35. The monthly mean concentrations [ppm] of CO for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years
(Note: Data for ANZ is not available.)

(3) Nitrogen Dioxide

Figure 36 shows that the regional variability of the magnitudes of the changes is relatively small: Almost all regions have rates of less than -10%, though the monthly mean concentrations widely vary from 1.0ppb to 100ppb (see Figure 37). Figure 36 also indicates that influences of the 450ppm policy on the reductions become larger in the longer term in almost all regions.

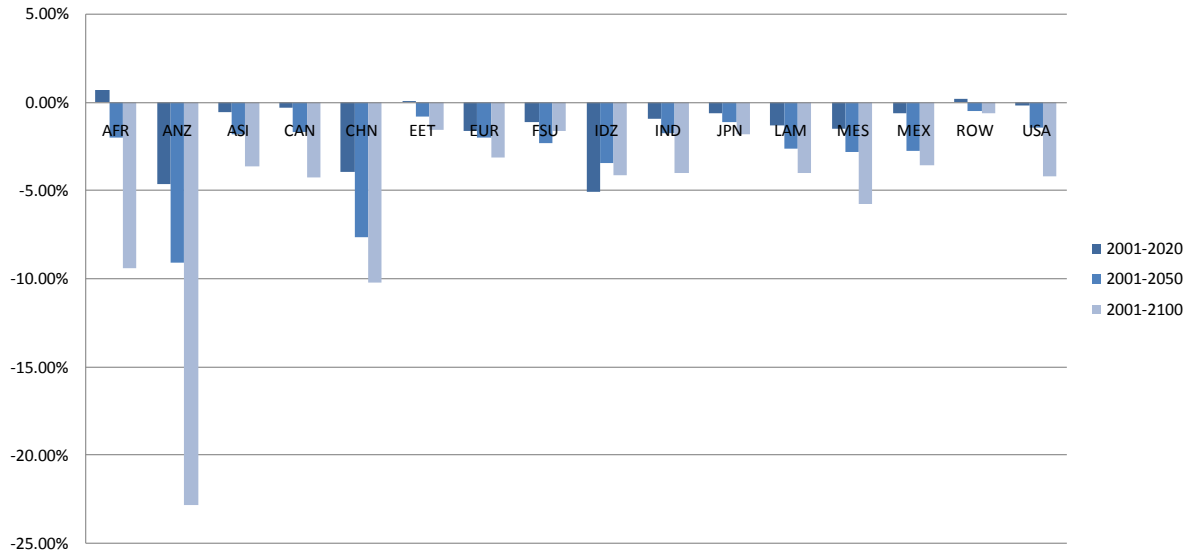


Figure 36 . The mean ratio of the differences of the monthly mean concentrations of NO_2 after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years

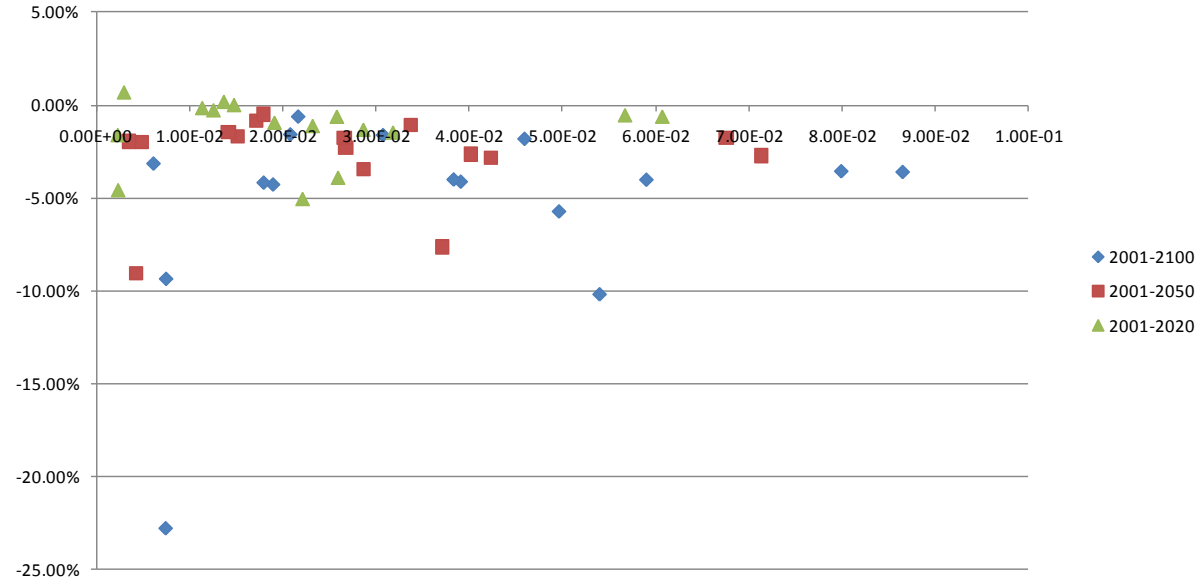


Figure 37. The monthly mean concentrations [ppm] of NO_2 for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

(4) Sulfur Dioxide

First, we will not consider the results for Australia and New Zealand (denoted "ANZ") as

they are not reliable. As shown in Figure 38, we see the substantial reductions in SO_2 as a result of the 450 ppm policy in all regions. Particularly, Canada, Western Europe, Japan, and the United States have reductions exceeding -80% for all of the three periods, where the concentrations are also higher as shown in Figure 39. Even in Africa and China, more than 20% can be potentially reduced by 2050. In China, the impacts can be -13.73% over 20 years, -27.58% over 50 years, and -39.69% over 100 years. The same is true for India and East Asian countries with higher income levels. With the 450ppm policy, India can potentially reduce SO_2 by -6.41% over 20 years, by -10.56% over 50 years, and by -16.57% over 100 years and East Asian countries with higher income levels would have reductions of -2.89% over 20 years, -6.86% over 50 years, and -8.68% over 100 years. The other countries or regions potentially have reductions of approximately -5%.

These substantial reductions in the concentrations can be partly explained by the larger reductions in emissions of SO_2. From Figure 40, we can see larger reductions in emissions of SO_2 by the 450ppm policy in Canada, Japan, and the United States. However, the reductions in Western Europe are only -20% by 2100. While Africa, Indonesia, and the Middle East reduce the emissions by more than -50% by 2100, their reductions in the concentrations are relatively small, less than -20%. This would indicate that while SO_2 is a primary pollutant and therefore, the reduction in its emissions contributes to the reduction in its concentration

in the atmosphere, some natural processes would also influence its concentrations in the air. While SO_2 is chemically stable, one representative removal path would be the reaction to H_2O, forming H_2SO_4. SO_2 can be also physically removed by wind if it's windy. Since the new Metamodel takes into account the meteorological conditions including rainfall and wind speed and their values vary by region by day, we could assume these meteorological conditions affect regional variability of the reductions in its concentrations. To verify this assumption, we will need further work to see regional variability of the meteorological conditions.

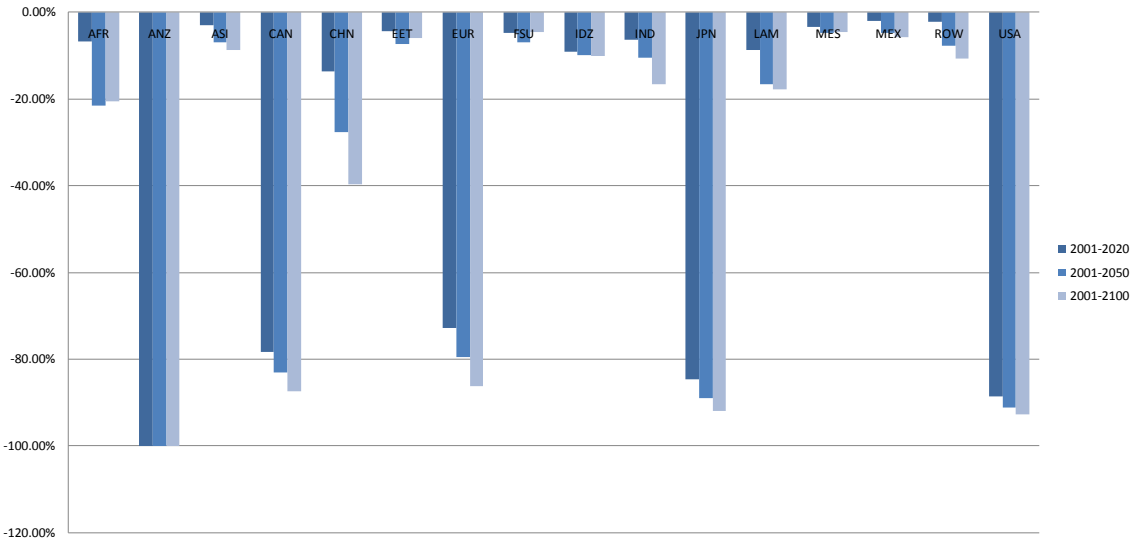


Figure 38. The mean ratio of the differences of the monthly mean concentrations of SO_2 after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years

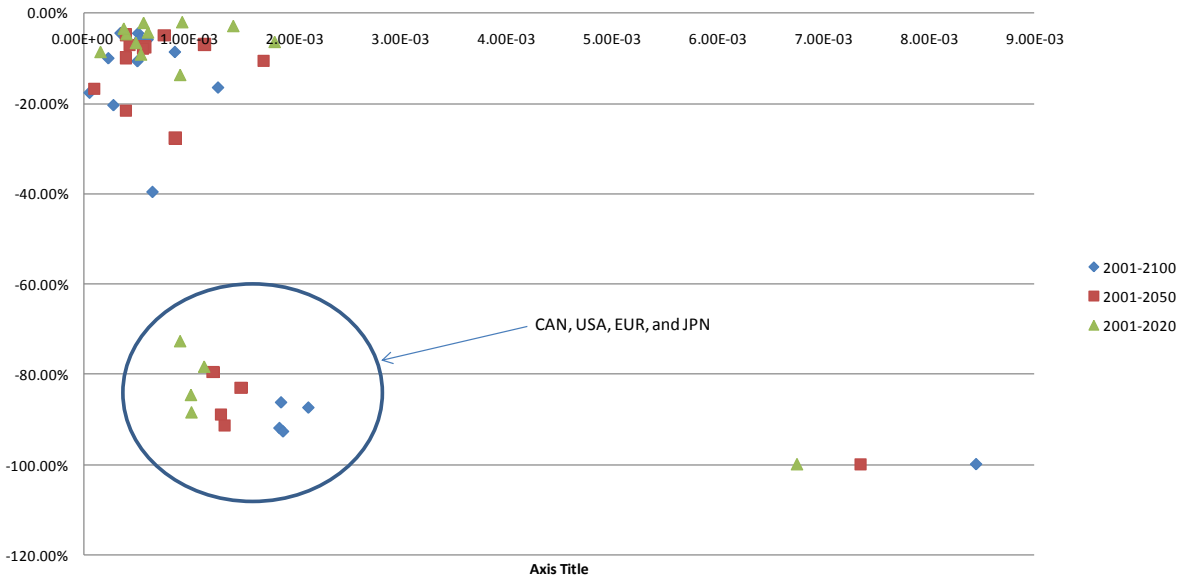


Figure 39. The monthly mean concentrations [ppm] of SO_2 for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

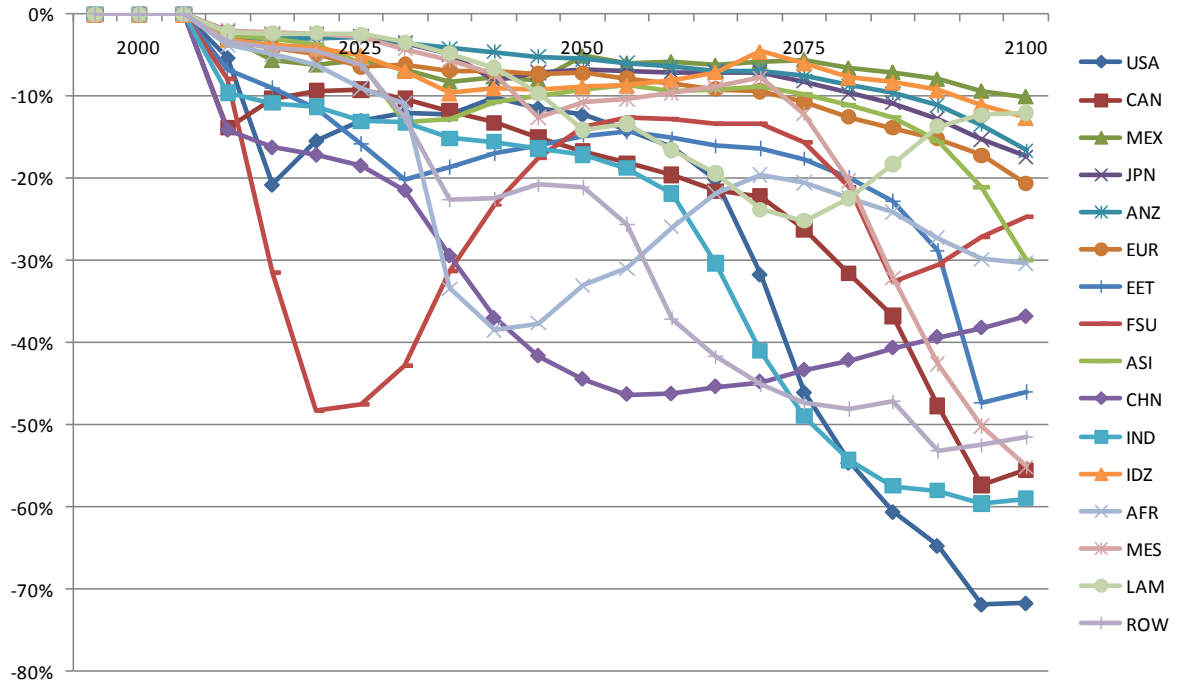


Figure 40. The reductions in the SO_2 emissions after the 450ppm policy by the EPPA regions for the 21th century

(5) Formaldehyde

From Figure 42, we can see the large variability of the percent changes as well as the monthly mean concentrations. The concentrations vary from 10ppt to 10ppb and the percent changes range from -15% to +5%.

From Figure 41, we also observe that, for many regions, more than twice as many EPPA regions show long term reductions than increases, though the magntitudes are less than 20% for all regions. In Africa and China, the reductions become greater in the longer term, similar to that of CO. The same is true in the cases for East Asian countries with higher income levels, Eastern Europe, India, Latin America, Middle East, and Mexico, though these countries would have reductions of less than -10%. In Indonesia, the reductions are approximately -10% for all periods. The exceptions are Canada, Western Europe, Japan, and the United States, where the 450ppm policy might increase the mole fractions of HCHO at least in the short term, though the degrees are small, less than 5%.

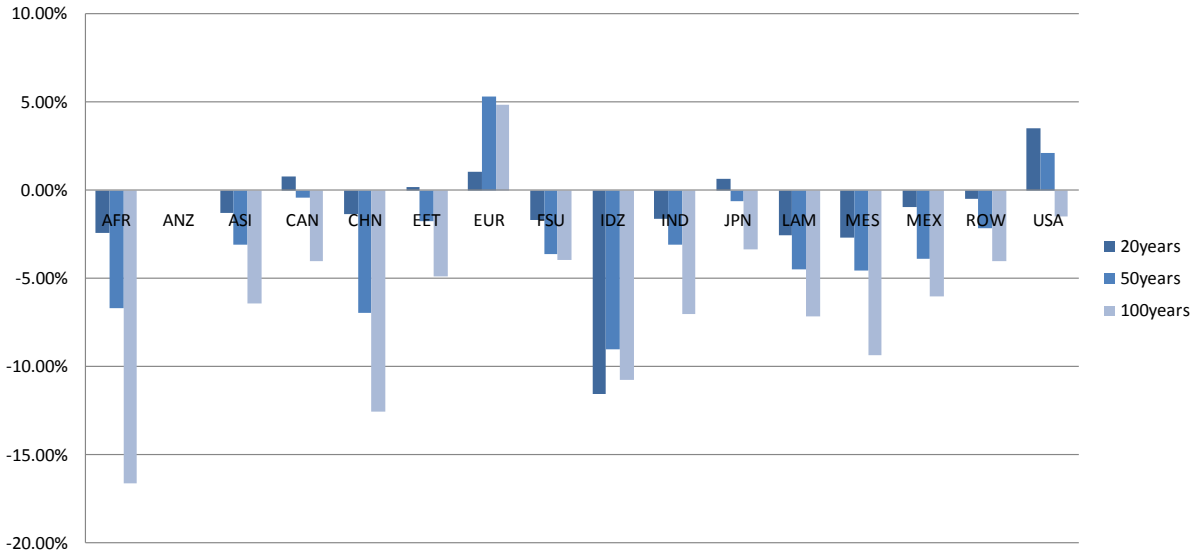


Figure 41. The mean ratio of the differences of the monthly mean concentrations of HCHO after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years

(Note: The data for Australia and New Zealand are not available because the analysis would be out of the appropriate range of simulations by the Metamodel.)

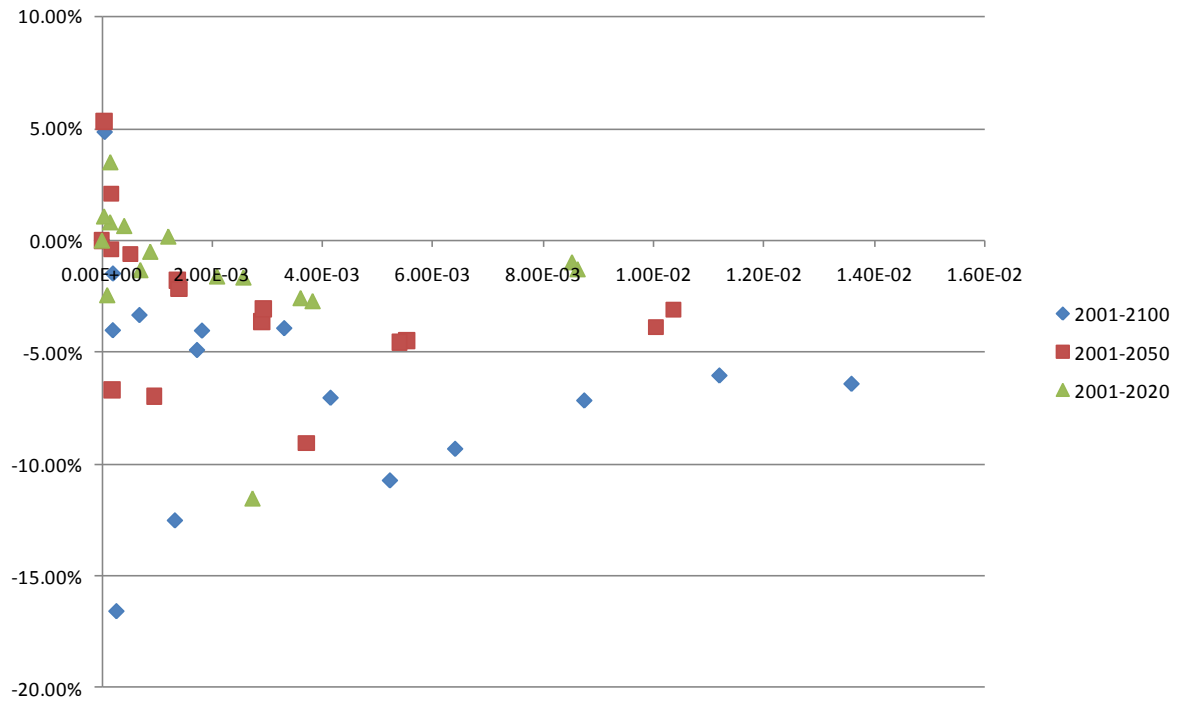


Figure 42. The monthly mean concentrations [ppm] of HCHO for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

(6) Sulfate Aerosols

While Figure 44 shows that the variability of both the concentrations and the percent changes are relatively small, we can see from Figure 43 that the largest reductions would occur in Australia and New Zealand, followed by Indonesia and India for the 100-year period.

The other regions potentially have less than -5% reductions. In terms of the temporal scale, the degrees of the reductions would not change significantly except those where the long-term changes would be positive, i.e. Canada, Eastern and Western Europe, Russia and former Soviet Bloc countries, Japan, and the United States. One possible explanation of the relatively small variability in addition to the small percent changes would be the reduced efficacy of the 450ppm policy for the reductions of sulfate aerosols, which are largely affected by the natural removal processes regardless of region.

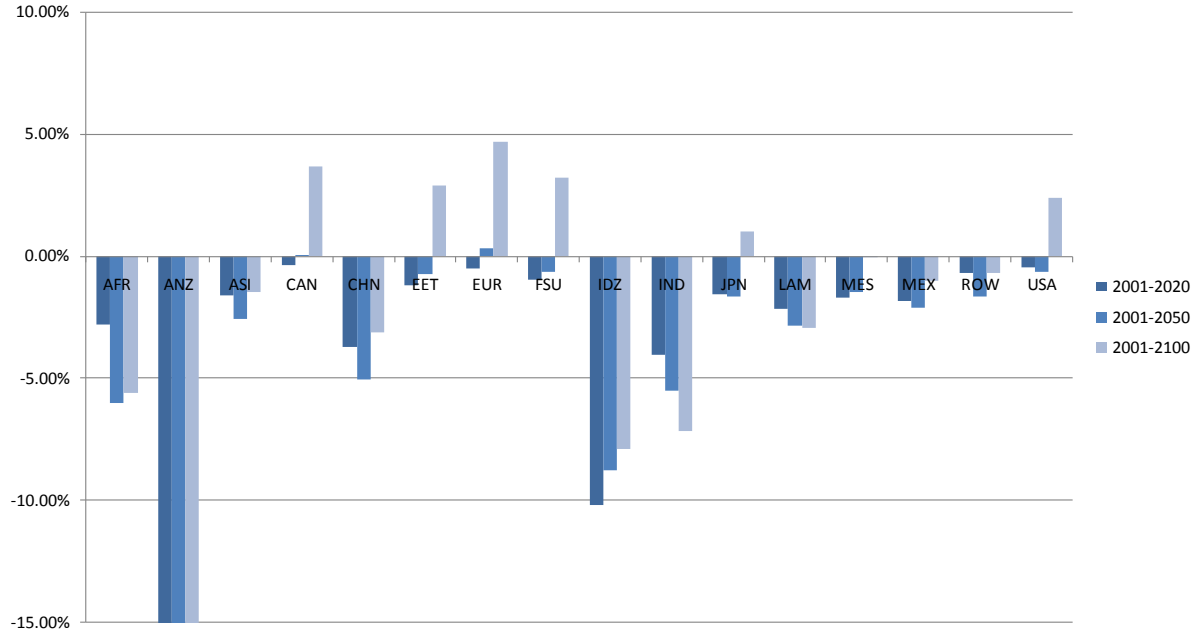


Figure 43. The mean ratio of the differences of the monthly mean concentrations of sulfate aerosols after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years

(Note: the data for Australia and New Zealand is approximately -80%. The exact numbers for the two countries are shown in Appendix A.)

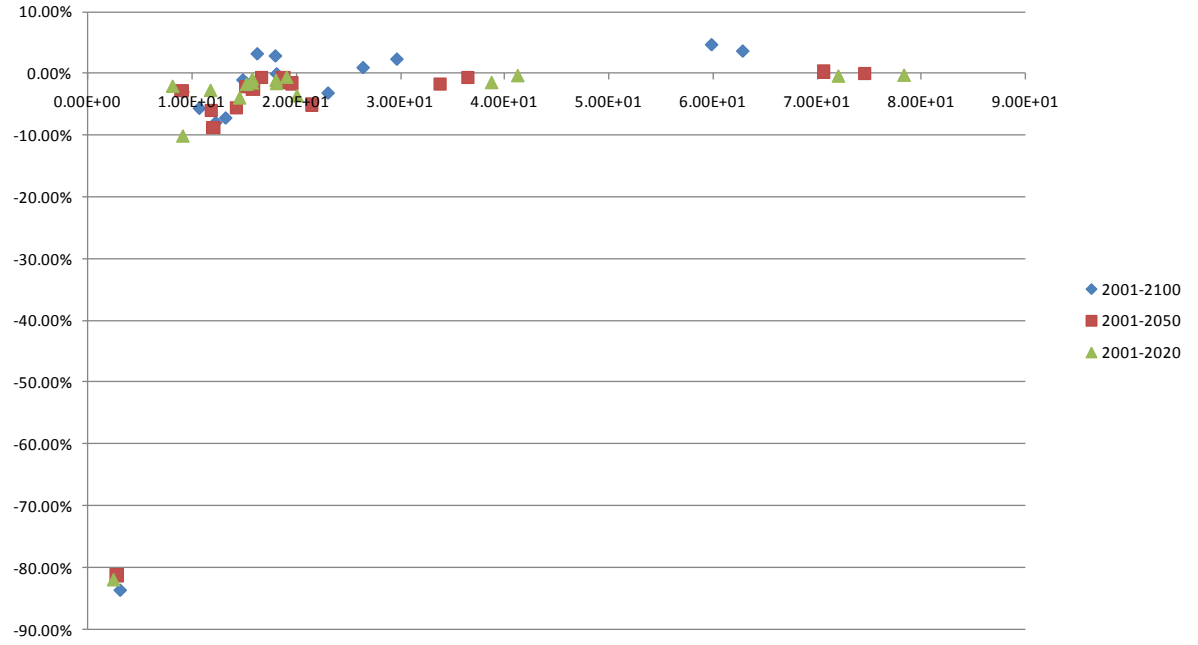


Figure 44. The monthly mean concentrations [ug/m^3] of sulfate aerosols for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

(7) Black Carbon

The magnitudes of the mean ratio of the differences widely differ by regions and by temporal scales as shown in Figure 45. Considering that the monthly mean concentrations are all approximately in the order of 1000[ug/m^3] (see Figure 46), we could assume the impacts of the 450ppm policy on black carbon would vary by region.

In terms of the magnitudes in Figure 45, most of the regions are likely to have significant reductions at least in the middle and long terms, except Canada, Western Europe, Japan, and the United States, which implies that highly developed countries will potentially see little benefit from the 450ppm policy. The results in Figure 45 are consistent with those in Figure 28 and Figure 29, which conclude that the averaged reduction is -15.7% at the global scale over 100 years. However, the impact of the 450ppm policy on the concentrations of BC should be examined in more detail, because the EPPA model estimates that emissions of BC decrease for the 21th century by the 450ppm policy

These conclusions imply that while Jacobson (2002) mentions the reduction of CO_2 emissions through a climate policy might increase emissions of BC, the concentrations of BC do not increase, but decrease.

In addition, we can observe from Figure 45 that the short-term impacts are negligible in almost all regions, and that the middle-term and long-term regional variability would be significant.

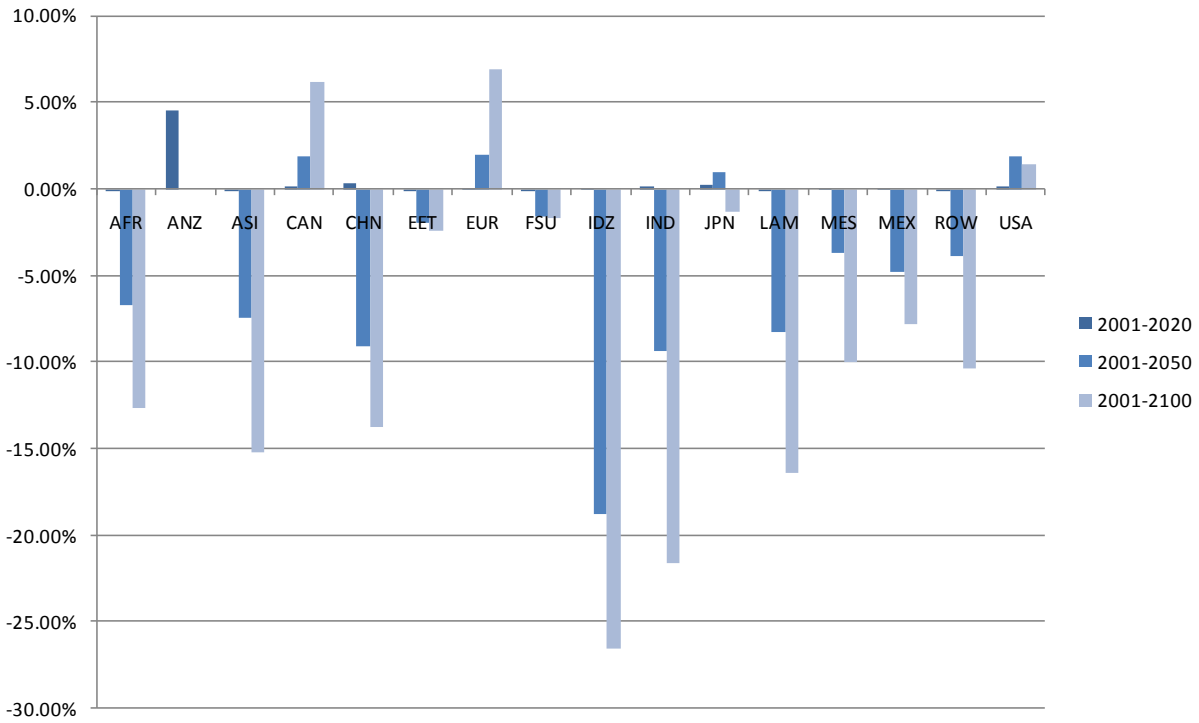


Figure 45. The mean ratio of the differences of the monthly mean concentrations of BC after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years
(Note: The data for Australia and New Zealand are not available.)

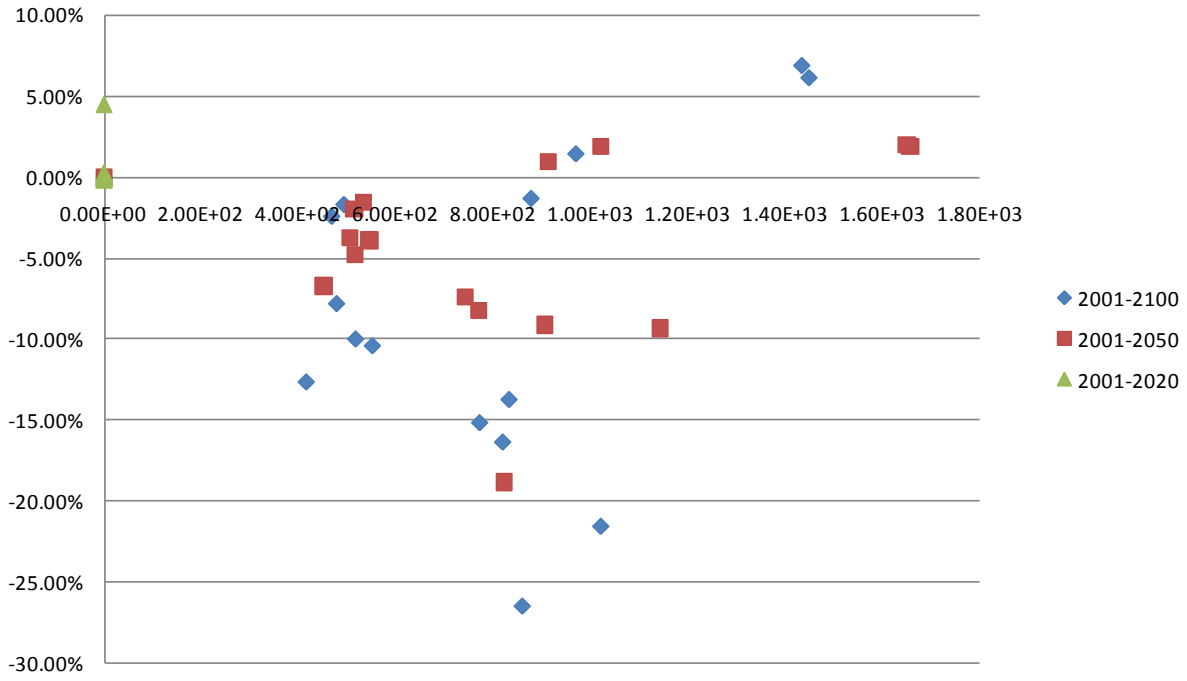


Figure 46. The monthly mean concentrations [ug/m^3] of BC for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

(8) Organic Carbon

From Figure 47, we see that the 450ppm policy can reduce OC concentrations, which vary widely by region and its concentrations are all within the range of 1,000 to 10,000 [ug/m^3] (see Figure 48).

More specifically, relatively larger reductions can be observed in highly developed countries, such as, Canada, Europe, Japan, and the United States. Indonesia potentially has more or less -20% reductions, and India would have the reductions of approximately -20% at least in the long term. On the other hand, the other regions, Africa, East Asia countries with higher

income levels, China, Eastern Europe, Russia and former Soviet Bloc countries, Latin America, Middle East, Mexico, and the rest of the regions, are seen to reduce OC by less than -20% by the 450ppm policy. Compared to sulfate aerosols and black carbon, however, the magnitudes of the reductions would not be substantially varied in those regions.

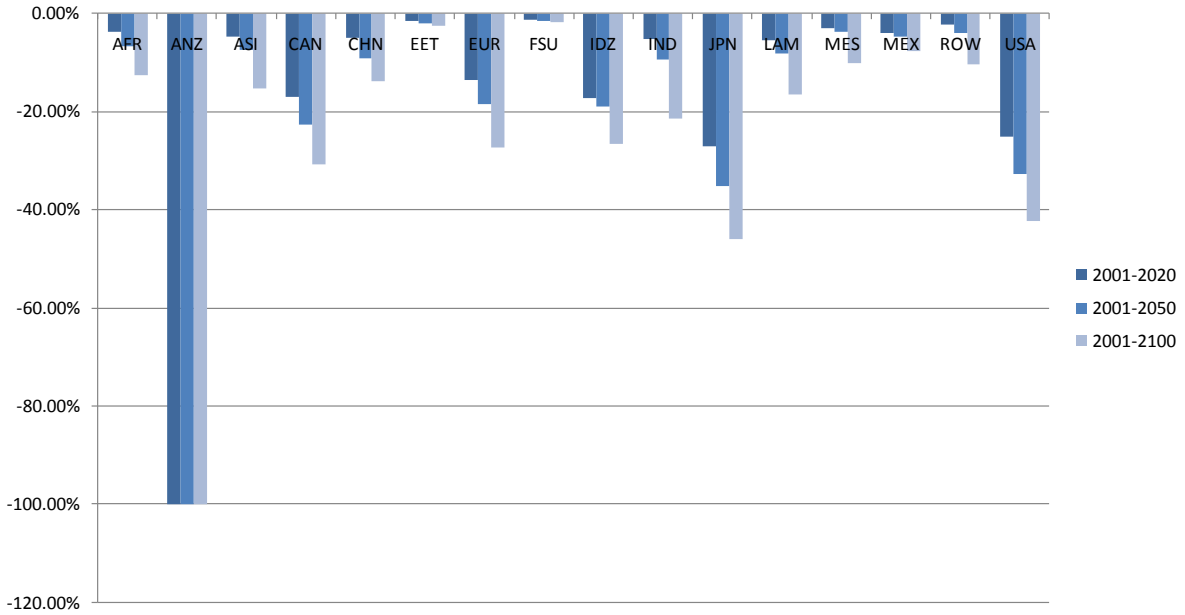


Figure 47. The mean ratio of the differences of the monthly mean concentrations of OC after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years

(Note: The data for Australia and New Zealand are not available.)

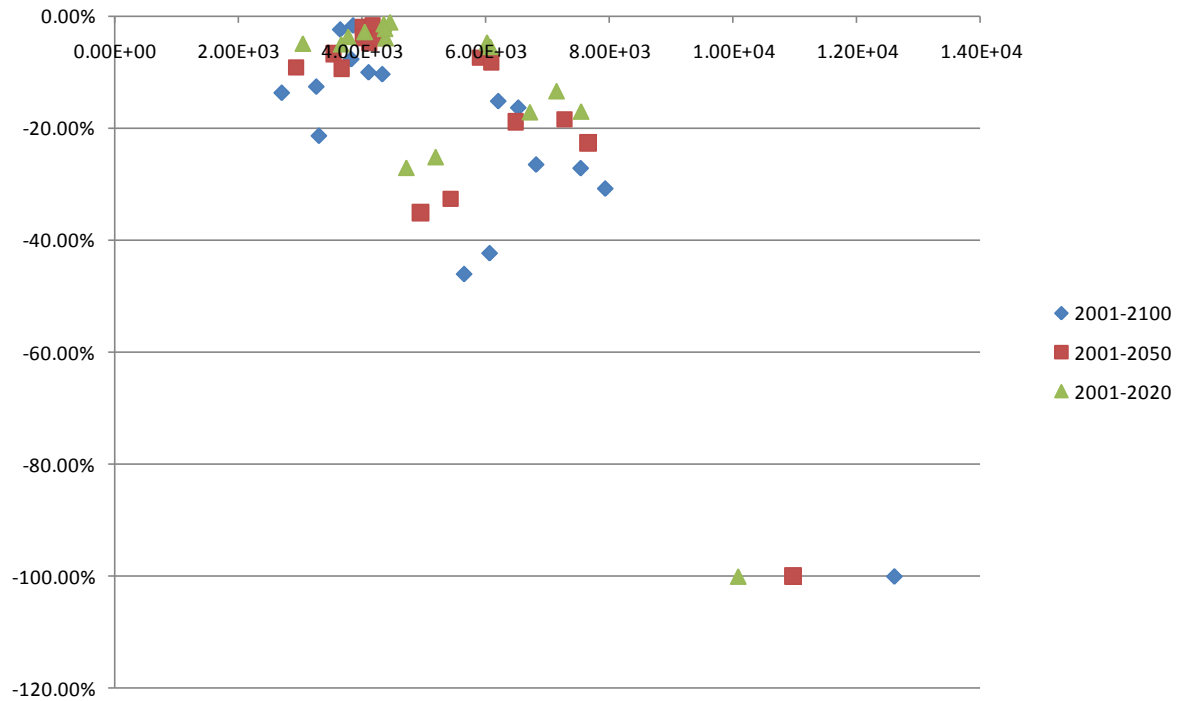


Figure 48. The monthly mean concentrations [ug/m^3] of OC for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

(9) Nitrate Aerosols

Finally, in Figure 49, we observe a large disparity in the trends of the mean ratio of the differences at the spatial and temporal scales and the concentrations also vary (see Figure 50). First, Canada, Eastern Europe, and Russia and the former Soviet Bloc countries are likely to increase the concentrations of nitrate aerosols, though the other regions reduce their concentrations in the long term. In particular, most of the regions would have reductions of less than -10%. However, China is likely to reduce concentrations by -16.19% for the 100-year period.

Second, in the short term, while all of the regions reduce its concentrations, the degrees of the reduction highly vary, ranging from -50% to nearly 0%. Specifically, while Canada, Western Europe, and Indonesia potentially reduce nitrate aerosols by -48.56%, -32.22%, and -10.09% respectively, the reductions in the other regions would be less than -5%.

Similarly to the analysis at the zonal scale, this large disparity in the trends could be explained by the entire chemical and physical processes to which meteorological variability by region have more or less influences.

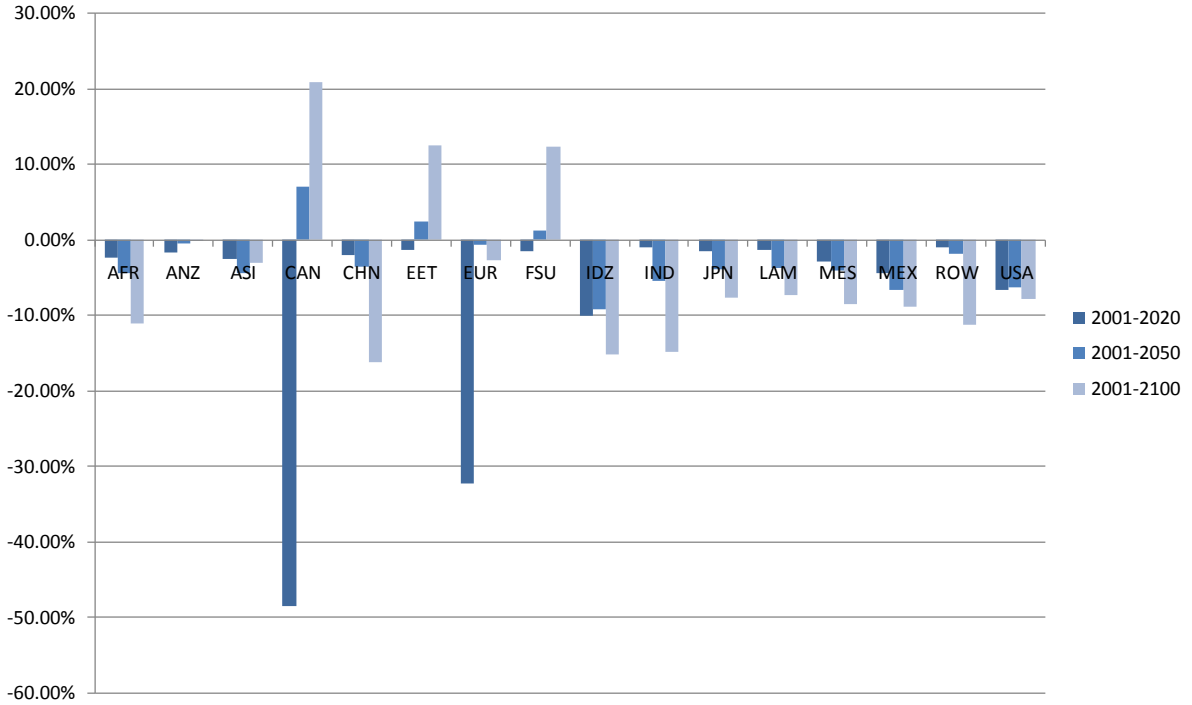


Figure 49. The mean ratio of the differences of the monthly mean concentrations of nitrate aerosols after imposing the 450ppm policy to the monthly mean concentrations for the no-policy case multiplied by 100% for the 3 different periods: 20, 50, and 100 years

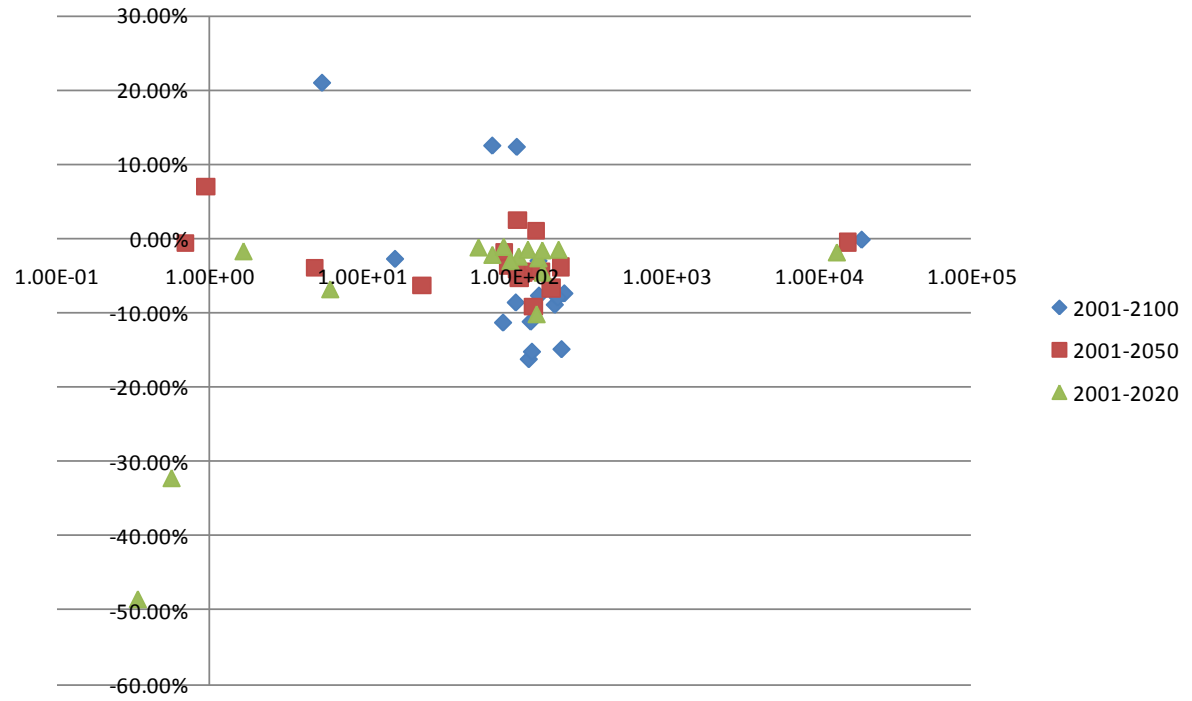


Figure 50. The monthly mean concentrations [ug/m^3] of nitrate aerosols for the no policy case (x-axis) relative to the mean ratios (in percentage terms) of the differences after the 450ppm policy (y-axis) for the 3 different periods: 20, 50, and 100 years

4.5.2. Stationarity

When comparing the data in terms of variability, the variance of the dataset itself should be considered because it would also cause uncertainties of the results. Figure 51 shows the standard deviation averaged across all regions for the first 12 months and the ratios of the standard deviations of the monthly mean concentrations averaged across the EPPA regions for the first 12 months to those for the 3 different periods for the no-policy and 450ppm policy cases. Each ratio is calculated in the following manner: 1) dividing the standard deviation of the monthly concentration for each of the three different periods by region by that for the first 12 months and 2) taking an average of the ratio varying by region.

It indicates the following points:

1) Sulfate aerosols, BC, OC, and nitrate aerosols have relatively greater standard deviations;
2) SO_2 and HCHO have relatively smaller standard deviations;
3) the averaged standard deviations become larger as the time period increases for all of the species;
4) while the large increase in the ratio for the 100-year period for nitrate aerosols would be skewed by large ratios in Japan for the no-policy and 450ppm policy cases, 531.64 and 831.78 respectively, the ratios for nitrate aerosols for the whole 21^{th} century are

still higher than for the other species;

The sources of lower stationarity are myriad. One will be due to the imperfect setup of the model, which would affect the analysis in the longer term; the current model does not consider influences of the daily outputs from the Metamodel on the global climate system. While they may not affect the global climate system significantly in the short term, the impacts might become non-negligible in the longer term, leading to irrational results. In addition, the smaller stationarity for aerosols including BC and OC would be caused by large contribution of meteorological conditions to formation, removal by air or deposition to the surface, as the new Metamodel includes the mechanisms associated with these processes.

	O_3		CO		NO_2		SO_2		HCHO	
	no policy	450ppm policy	no policy	450ppm policy	no policy	450ppm policy	no policy	450ppm policy	no policy	450ppm policy
Averaged Standard Deviation in 2001	2.43E-03	2.67E-03	2.32E-02	2.40E-02	1.48E-03	1.47E-03	2.83E-04	1.81E-04	1.78E-04	1.87E-04
20 years	3.20	2.72	2.01	1.82	2.19	2.12	1.16	1.03	1.77	1.73
50 years	7.32	6.33	4.47	3.77	5.46	5.18	1.37	1.20	4.07	3.65
100 years	14.20	12.29	6.51	5.26	9.05	8.41	1.86	1.37	6.16	5.03
	Sulfate aerosols		BC		OC		Nitrate aerosols			
	no policy	450ppm policy	no policy	450ppm policy	no policy	450ppm policy	no policy	450ppm policy		
Averaged Standard Deviation in 2001	1.27E+01	1.34E+01	3.07E+02	3.07E+02	1.37E+03	1.23E+03	3.16E+01	3.18E+01		
20 years	1.59	1.59	0.00	0.00	0.90	0.93	1.61	2.30		
50 years	1.43	1.25	0.96	1.05	0.99	1.04	3.75	7.80		
100 years	1.47	1.30	1.25	1.25	1.32	1.25	56.63	100.18		

Figure 51. The standard deviation averaged across all regions for the first 12 months and the ratios of the standard deviations of the monthly mean concentrations averaged across the EPPA regions for the first 12 months to those for the 3 different periods for the no-policy and 450ppm policy cases
(Note: Figure is created based on the tables in Appendix A and the data excluded the results for ANZ.)

4.5.3. Summary

The findings from the comparisons between the no policy and the 450ppm policy cases in Figure 33 through Figure 51 can be summarized as below in terms of the temporal and regional variability in the impacts of the policy.

1) The 450ppm policy is likely to contribute to reducing key air pollutants except O_3 and as a result, the regional and temporal variability affected by the 450ppm policy may not be an important issue, as the changes by the policy would be almost negligible.
2) However, it can contribute to reducing nitrate aerosols and sulfate aerosols at the regional scale, unlike the conclusion at the zonal scale.
3) The variability associated with the types of species is significant. Compared to the other 8 species, the magnitude of the reductions would be largest for SO_2: more than -10% for all regions for all periods; organic carbon: at least more than -10% for the 100-year period; nitrate aerosols, HCHO, Sulfate aerosols, and Black carbon: approximately -5% at least for the 100-year period. However, O_3, CO, and NO_2 would be much less affected by the 450ppm policy even for the longest period: less than -5%.
4) In terms of the temporal variability in the magnitudes of the changes, all species except SO_2 and sulfate aerosols are relatively large and the degrees of the reductions

become greater for the longer period, which would imply that the air-quality effects of the 450ppm policy could become larger as time advances.

5) Conversely, the temporal variability in the magnitudes for SO_2 and sulfate aerosols would remain relatively constant. This implies that some of the air-quality effects of the 450ppm policy can be attained immediately.

6) The magnitudes of the changes vary widely by region. Some species such as SO_2 and Organic carbon would be reduced more in highly developed regions such as Western Europe and the United States, whereas some, such as black carbon and HCHO would be reduced more in developing regions such as China and India.

7) Finally, the variability of the results for SO_2 and nitrate aerosols may be highly nonstationary compared to other species, taking into account the large statistical uncertainties of the monthly mean concentrations.

Chapter 5. Implications for Policy Design for Air-quality Co-benefits

As stated in Section 2.3.2., there are three issues to be clarified in order to successfully integrate air-quality co-benefits into climate change mitigation options. Chapter 4 aimed to address assessments of air-quality co-benefits, particularly focusing on revealing the regional, temporal, and pollutant-specific variability in the key air-quality impacts of climate policy. This chapter, in turn, aims to provide implications for policy design for integrating air-quality co-benefits in a future international framework.

5.1. Challenges for Assessing Air-quality Co-benefits

5.1.1. Approaches for Assessing Air-quality Co-benefits

The methodology for evaluating co-benefits is twofold: the top-down approach and the bottom-up approach, as shown in Table 7. The top-down approach normally utilizes partial or general equilibrium computational models. While the model is normally comprehensive so that it represents as many countries, industry sectors, and key factors in the natural and socio-economic system as possible, for the sake of simplicity it captures detailed or local differences less well. The bottom-up approach generally evaluates the values of co-benefits by constructing models for a specific industry sector or project for climate change mitigation

by collecting the actual data. This approach enables a more detailed representation of system characteristics based on actual data, though it is less comparative due to the specificity.

	Description	Advantages	Disadvantages
Top-down approach	Partial or general equilibrium model	Comprehensively represent natural and socio-economic system on a large scale	Less well captured detail variances, though ancillary effects may vary locally or regionally
Bottom-up approach	Aggregated data of an actual project or case study	Represents a system well by using actual data	Less comparative to other studies

Table 7. The Comparison of the Top-down and the Bottom-up approaches
(Created by the author by referring to (Pearce, 2000; Pittel Rübbelke, 2008; G F Nemet, 2010))

5.1.2. Methodological Challenges for Assessing Air-quality Co-benefits

While there are a number of relevant studies, their study scopes, underlying assumptions and experimental conditions differ widely. The IPCC's FAR (B. Metz O. D., 2007) approach indicates underlying assumptions for baseline scenarios associated with policies, economic conditions, technological innovations and ecological conditions, for instance, as well as political decisions on when and what policies are implemented. It also examined which countries, industry sectors and air pollution control policies are included in baseline scenarios, as well as what technology options are represented in baseline and policy scenarios and what time horizons are applied. These differences make it complicated to make comparisons between studies. The following summarizes the sources of differences in the assessments of

air-quality co-benefits.

The first source of differences is the selection of time horizons. Some studies focus on assessments up to 2030, some cover the period up to 2050 and others only up to 2010. As pointed out by the IPCC (B. Metz O. D., 2007), this is critical, because air pollution reduction is assumed to occur in a shorter term and at a smaller scale as compared to global climate change mitigation, which is believed to have influences in the longer term and at a global scale. Table 8 shows that the current major integrated assessment models have set different time horizons (G F Nemet, 2010).

Table 1. Treatment of AQ co-benefits in integrated assessment models of climate change policy.

	Venue	Model name	Time	GhG emissions	Value climate impacts	Estimate AQ co-b.	Value AQ co-b.	Include in final values
A	IPCC	IMAGE[a]	2100	Yes	No	No	—	—
B	IPCC	MERGE[a]	2150	Yes	No	No	—	—
C	IPCC	MESSAGE[a]	2100	Yes	No	No	—	—
D	IPCC	MiniCAM[a]	2100	Yes	No	No	—	—
E	IPCC	SGM[a]	2050	Yes	No	No	—	—
F	IPCC	WIAGEM[a]	2100	Yes	No	No	—	—
G	Nordhaus (2008)	DICE-2007[b]	2200	Yes	Yes	No	—	—
H	UK	C.C. Act of 2008 Assessment (MARKAL)[c]	2050	Yes	Yes	Yes	Yes	Yes
I	UK	Stern 2005/PAGE2002[d]	2200	Yes	Yes	Yes	Yes	No
J	US	C.B.O. (2009)[e]	2019	No	No	No	—	—
K	US	EIA NEMS (2008)[f]	2030	Yes	No	No	—	—
L	US	EPA ADAGE (2008)[g]	2050	Yes	No	No	—	—
M	US	EPA IGEM (2008)[g]	2050	Yes	No	No	—	—

[a]IPCC (2007). [b]Nordhaus (2008). [c]DECC (2008). [d]Stern (2006). [e]CBO (2009). [f]EIA (2008). [g]EPA (2008).

Table 8. Examples of the Integrated Assessment Models of Climate Change Policy
(Source:(G F Nemet, 2010))

The second one is a selection of spatial scales. The evaluations of air-quality co-benefits vary by spatial scales (Rob Swart, 2004). Many studies cover only specific countries (Pearce, 2000; Pittel Rübbelke, 2008; G F Nemet, 2010). The third one is a selection of species

included in the assessments. Each study selects different sets of air pollutants for which the impacts of climate change mitigation were investigated in particular countries (Pearce, 2000; Pittel Rübbelke, 2008; G F Nemet, 2010).

Next, selection of technological options also makes assessments incompatible. Estimating air-quality co-benefits has to include a wide range of substituting possibilities, assumptions on technological change and a clear representation of current environmental legislation. For instance, they point out that substituting more fuel-efficient diesel engines for petrol engines might lead to higher PM/black carbon emissions (Kupiainen, 2007). Finally, differences in local conditions such as meteorology, topography, and the densities and distributions of population, crops, materials, or other affected assets may influence the value of co-benefits (Pearce, 2000).

5.1.3. Regional Variability of the Economic Values of Air-quality Co-benefits

Nemet (2010) conducted extensive surveys of past peer-reviewed literature on air-quality co-benefits of climate policies (Figure **52**). They demonstrated that economic values of air-quality co-benefits in developing countries are larger than those in developed countries as shown in Figure 53 (G F Nemet, 2010). Specifically, he indicates that while the overall range, mean, and median values of the air quality co-benefits of the climate policy is \$2-128/tCO_2,

$44/tCO_2$, and $31/tCO_2$ [2008$] respectively for developed countries, those for developing countries are $27-196/tCO_2$, $81/tCO_2$, and $43/tCO_2$ [2008$] respectively. Morgenstern (2000) also argues in favor of the variability of economic values of air-quality co-benefits, implying that ancillary benefits from climate policies in developing countries are significantly larger than in the U.S (Morgenstern, 2000).

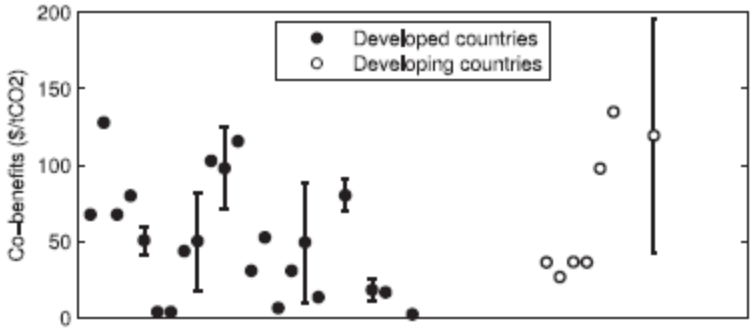


Figure 52**.** Estimates of the value of air quality co-benefit in developed (left) and developing countries (right) in 2008$/$tCO_2$. (Note: Within each category, data are reported from left to right by date of study (1991-2010). Absence of values indicates a co-benefit study for which health impacts were assessed, but valuation in $/$tCO_2$ was not assessed.) (Source: **(G F Nemet, 2010)**)

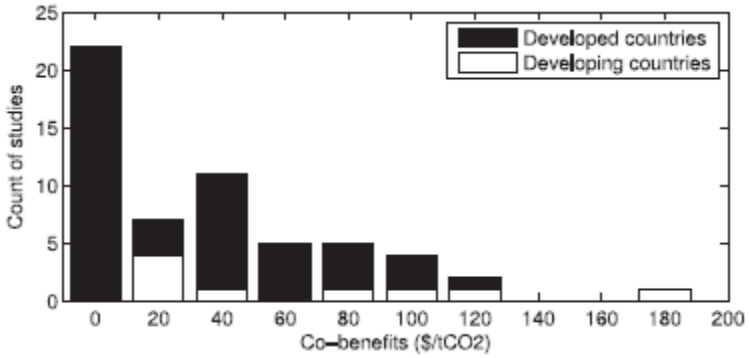


Figure 53. Frequency of values reported in air quality co-benefits studies.
(Source: (G F Nemet, 2010))

5.2. Policy Design for Integrating Air-quality Co-benefits

Climate policy is technologically related to urban air pollution control policy. As many

studies have demonstrated, climate policy is directly or indirectly linked to certain types of low-carbon technologies, though it depends on what type of climate policy is adopted. Most of the existing air pollution control policies, however, almost identically determine types of technologies. Some selected technologies, however, can reduce the emissions of not only CO_2 but also air pollutants, but some reduce the emissions of SO_2 as well as increasing the CO_2 emissions.

There are two categories of policy options: command-and-control options and market-based options, though the governments often set voluntary agreements or guidelines for emitters, which are not mandatory.

(1) Command-and-Control options: Technology-based or Performance-based Standards.

(2) Market-based approach options: Taxes and Tradable Permits.

5.2.1. Effects of Integrating Air-quality Co-benefits on Standards

There are two types of standards: technology-based standards and performance-based (emission-based) standards. While the market-based instruments have become more common, performance standards have been the most commonly used regulations for environmental problems. These include regulations such as the CAFE[20] standards in the United States and

[20] The Corporate Average Fuel Economy

the EURO[21] standards in the EU, both of which regulate the fuel economies of on-road vehicles.

Technology standards determine specific types of technologies for reducing GHG or air pollutants. Private firms emitting pollutions have to use the specified technologies. It may cause 1) fewer incentives for them to innovate better and cheaper technologies and 2) inefficiency in reducing GHGs and air pollutions as one technology does not necessarily reduce all of the harmful species, but does reduce only targeted ones. The first case may result in failing to reduce the future emissions of GHGs and air pollution in a better and cheaper way, whereas the latter case may bring about expected benefits –reductions of harmful species – at a determined cost.

On the other hand, emission standards may not necessarily take into account ancillary effects of adopted technologies. A power plant may adopt a technology enabling the reductions of SO_2 to meet the cap on SO_2 emissions. However, it is possible to ignore the ancillary effects of the adopted technology such as the reduction of PM. In other words, while the standards can be a compelling force to reduce targeted species in either scheme, technology-based standards may cause the inefficient use of financial resources and emission-based standards

[21] European Emission Standards

may overestimate the costs necessary to obtain expected benefits (Pearce, 2000).

5.2.2. Effects of Integrating Air-quality Co-benefits on Taxes

Assume that a primary objective is to control CO_2 emissions and reducing/increasing emissions of air pollutants is an ancillary effect of making it consistent with the scope of the study. With respect to climate change mitigation, a carbon tax is a tax on a transaction, setting a price for CO_2 emissions. Since fewer emissions of CO_2 allow emitters to pay fewer taxes, it creates incentives for the reduction of fossil fuel consumption and for deploying cleaner energy sources.

As such, suppose that no ancillary effect is taken into account. A tax on a negative externality, i.e., emitting CO_2 into the atmosphere, should equal the marginal damage costs, which should be also equal to the marginal mitigation (=abatement) costs. In other words, Carbon Tax equals Marginal Damage Costs equals Marginal Mitigation Costs. Then, suppose that ancillary effects, i.e., air-quality co-benefits, are considered. A carbon tax is equal to the sum of the marginal damage costs and marginal ancillary benefits, as shown in this formula:

Carbon Tax = Marginal Damage Costs + Marginal Ancillary Benefits = Marginal Mitigation Costs..

Compared to the case that does not take into account air-quality co-benefits, the carbon tax on air-quality co-benefits becomes higher and, simultaneously, the level of CO_2 mitigation will become higher. In other words, including air-quality co-benefits increases the carbon price.

In reality, however, Pearce (2000) argues that the ancillary effects will be already the subject of separate policies, i.e. to reduce acidification and eutrophication from NOx, SOx, NH_4 and VOCs, so as to reduce noise nuisance and traffic congestion, etc. In that case, the incremental price of a carbon tax relevant to the marginal ancillary effect is not the incremental marginal damage cost, but the avoided costs that are supposed to be covered by the policies directly subject to the ancillary effects (Pearce, 2000).

The other types of taxes relating to carbon taxes are an emission tax and an energy tax. An emission tax on GHG emissions requires individual GHG emitters to pay a charge or tax for every ton of GHG emissions[22]. The carbon tax is an emission tax when it is subject only to the CO_2 emissions. An energy tax increases the price of energy uniformly, regardless of the emissions produced by the energy source. Considering the energy source normally has externalities other than emissions of CO_2 such as emissions of air pollutants. With respect to the inclusion of all of the externalities of the energy source including the emissions of air

[22] http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch13s13-2-1-2.html

pollutions, there should be no ancillary effects.

In reality, the ancillary effects have not been integrated into the carbon/energy tax. Pearce (2000) argues that the reason why the ancillary effects are not considered in tax design is that the size of the tax is determined not only by environmental impacts but also by perceptions about cost burdens, competitiveness and equity impacts(Pearce, 2000).

5.2.3. Effects of Integrating Air-quality Co-benefits on Tradable Permits

A tradable permit sets a quantitative target of emissions of a regulated species. As a carbon tax that accounts for air-quality co-benefits should be higher than a carbon tax without air-quality co-benefits being taken into account, an emission target should become stricter. In other words, a lower quantity of tradable permits will be available once ancillary effects are considered. On the other hand, the price of a permit, which theoretically equals the marginal mitigation cost, will become higher once air-quality co-benefits are considered.

However, as Pearce (2000) claimed, it is not clear how far geographical sensitivity over the ancillary effects of a GHG control will influence what the tradable permit scheme should be (Pearce, 2000). In fact, as demonstrated in Chapter 4, air-quality co-benefits are significantly location-specific. In addition, there would be ancillary effects of a GHG control other than

air-quality co-benefits. Therefore, the feasibility and accountability of including air-quality co-benefits is still unjustified. Nevertheless, increasing attention to the consideration of air-quality co-benefits for the Clean Development Mechanism (CDM) projects have recently arisen as the co-benefits would be expected to get developing countries interested in climate change negotiations and the CDM is expected to be a key instrument in realizing co-benefits.

Finally, while it is described how co-benefits affect each single policy instrument, the governments often select not a single policy measure, but rather create a portfolio of several policies.

5.3. Barriers to Implementation of Air-quality Co-benefits into Policy Design – Case of the CDM scheme

While the Clean Development Mechanism (CDM) and the bilateral cooperation schemes are implementing co-benefits, there are still barriers.

The first barrier lies in the existence of few rationales beyond international cooperation. Developing countries will benefit from any CDM projects at least in reducing GHG emissions, regardless of whether they have additional benefits such as reducing air pollutants, etc. Even without reductions on air pollutants, efforts to reduce GHGs will contribute to them.

However, from the perspective of the ANNEX I[3] countries, any efforts at implementing co-benefits cannot be converted to monetary rewards within the current framework. In other words, there is no rule to count air-quality co-benefits achieved simultaneously by a CDM project in Certified Emission Reductions (CERs). This means that any ANNEX I countries cannot utilize air-quality co-benefits to achieve their own emission targets as determined by the Kyoto Protocol. In fact, the Ministry of the Environment, Japan (MOEJ)'s Co-benefit Approach Model Project[23] and the Integrated Environmental Strategies (IES) program in the United States seem to be operated primarily for the purpose of international cooperation.

The second barrier is that there are few incentives for the private sector. From the perspective of the private sector, few incentives exist associated with air-quality co-benefits. Under the current CDM scheme, reducing the GHG emissions can produce CERs for the CDM project developer. The private company, then, sells the credit in the emission trading market through bilateral agreements to those who need emission permits. However, the current CDM scheme has neither an adequate framework for taking into account co-benefits nor for converting the contribution to co-benefits into monetary values nor does it include a scheme to maximize co-benefits. Therefore, no matter how much a private developer increases co-benefits of a CDM project, there is no additional gain for the developer. Therefore, although Japan's

[23] The official website is http://www.kyomecha.org/cobene/e/index.html. The following website also described detailed information for applications for the program. http://www.env.go.jp/water/info/cdm/index.html

subsidy program would lower the entry barriers to developing CDM projects, it would not fundamentally contribute to improving the market competitiveness of the private developer (Nishikawa, 2008).

The third barrier is that no globally-standardized criteria for measuring co-benefits and for designing CDM projects with co-benefits yet exists. While the MOEJ's manual and the IES's handbook contain guidelines for measuring and implementing co-benefits into existing or new regulations, they are separated and not approved by the international community. Even when air-quality co-benefits are implemented, transaction costs may increase due to the variability of air-quality co-benefits. As demonstrated in Chapter 4, air-quality co-benefits differ spatially, temporally, and specifically at least from a physical viewpoint, which will cause difficulties in their monetization.

5.4. Implications for Policy Design for Air-quality Co-benefits

Many international and regional organizations, for example, the Global Atmospheric Pollution Forum[24], have recently discussed how to develop a framework for integrating

[24] The Forum is a partnership of the following organizations: the United Nations Environmental Programme (UNEP); the United Nations Economic Commission for Europe (UNECE), Convention on Long-range Transboundary Air Pollution (LRTAP); the Air Pollution Information Network for Africa (APINA); Inter-American Network for Atmospheric and Biospheric Studies (IANABIS); the Clean Air Initiative (CIA); Sahara and Sahel Observatory (OSS); the Institute for Global Environmental Strategies (IGES); the International

air-quality co-benefits (Kuylenstierna, Mills, & Hicks, 2010). As stated in Section 4, although the integration of air-quality co-benefits theoretically increases the price of carbon tax or the price of a tradable permit, to what degree the prices can be increased depends on the degrees of air-quality co-benefits. To alleviate these barriers, this section analyzes these implications, particularly, enhancing further discussions over possible solutions for the development of a global framework for including air-quality co-benefits.

First of all, the magnitude of the impact of a particular climate policy would vary by pollutant. Some increase, some are reduced. Even though a pollutant is likely to be reduced by the policy, the degree of reduction may differ by pollutant. However, the concentrations in the air are not necessarily correlated to the degree of actual damage, as measured by increasing mortality or greater damage done to nature. Furthermore, the criteria of the existing air-quality standards should differ by countries as briefly introduced in Chapter 2. There are still countries that have not regulated air pollutants enough yet. Nevertheless, the pollutant-specific variability of the policy impacts would suggest that a climate change mitigation option can take into account air-quality co-benefits at least with respect to pollutants which can be effectively reduced by the mitigation option in international and national negotiations.

Union of Air Pollution Prevention Associations (IUAPPA); and the Stockholm Environment Institute (SEI).

Second, the regional variability is also significant. For instance, air-quality in China could benefit more than in the other regions, because more types of the pollutants are likely to be reduced by the 450ppm policy in the country. The same would be true in India and Africa, but some species such as SO_2 can be far more effectively reduced in highly developed countries. For instance, black carbon has recently received attention for having a global warming effect. Research on black carbon shows that the impact would vary from +5% to -25%, even though the statistical uncertainties of the monthly mean concentrations are 12~26%, not greater compared to those for the other species. One implication for the policy space is that it is challenging to take into account air-quality co-benefits in an internationally-integrated scheme for climate change mitigation without taking into account the regional variability. Adversely, if regional variability is small or negligible but air-quality co-benefits exist, the species may be better adapted to being integrated into climate change mitigation options at the international level.

Third, the temporal variability implies that co-benefits of the climate policy would be realized in the shorter term for some species, for instance, SO_2. If air-quality co-benefits are monetized or at least quantified, this variability may allow discount rates to be differentiated by species.

Fourth, significant non-stationarity with respect to the monthly mean concentrations for the 'no policy' case indicate that geological, meteorological, and ecological variability may significantly influence how to set baselines. For pollutants that exist at significant levels, this variability may not be capable of being integrated. For instance, sulfate aerosols, black carbon, organic carbon, and nitrate aerosols have relatively greater standard deviations, though SO_2 and HCHO have relatively smaller standard deviations. For pollutants of which standard deviations of the monthly mean concentrations significantly vary as the time period increases, this variability may make it challenging to set an appropriate time horizon. For instance, nitrate aerosols would not be less suitable from the second viewpoint as its standard deviations both for the no-policy and 450ppm policy cases substantially increase by 2100. Instead, sulfate aerosols, black carbon, and organic carbon could be more suitable as their standard deviations vary less significantly.

Chapter 6. Conclusion

The issue of air-quality co-benefits is not new. However, there is very little relevant literature on the assessments on air-quality co-benefits in a manner that can compare them across regions. While theoretically it has been pointed out it is crucial for air-quality co-benefits to take into account geographical variability, this study explicitly estimates the regional and temporal variability of the air-quality co-benefits of a climate policy for several species at the global scale using a newly developed detailed "Metamodel" of chemical and physical processing, established the required linkages to the IGSM, and utilized the preliminary offline version of this IGSM-Metamodel for detailed pollutant assessments under no-policy/policy climate scenarios.

For the Metamodel interactively communicating with the IGSM and the EPPA model, the following points should be clarified.

1) China and India were assigned to their respective city type within the Metamodel for the entire period of model integration (i.e. the 21th century). Yet both countries should likely have had some of their cities assigned to the "Developed" city type at some point during the simulation period. The same will also be true with respect to some of the developed countries.

2) The current offline version of the metamodel does not consider possible future cities. A grid is identified as an urban area if NOx emission are not zero. However, NOx emissions for future years are calculated by multiplying the NOx emission values from 1997 by the factors calculated based on the region-specific emission data of the EPPA model. And since the 1997 data from the NOx emissions is zero, if a grid is not identified as urban in 1997, no grid that is not urban in 1997, but has subsequently grown and now exceeds 5kgN/day/km^2 in the future is included. Therefore, it is highly likely that more urban areas are ignored for future years and that the concentrations of the air pollutants might be underestimated for future years.

Finally, this study focused on only one side of a coin: the air-quality co-benefits of a climate policy. As demonstrated in Chapter 1, the global climate system may be also affected by urban air pollution. The previous version of the urban airshed model was utilized to help researchers understand the impact of urban air pollution on global climate change (Sarofim, 2007). Thus, once implemented within the fully coupled version of the IGSM, this new Metamodel will be able to provide a new perspective on the interactions between the two.

Appendix A

(1) Tropospheric Ozone

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	7.60E-02	7.60E-02	-3.17E-05	-0.04%	2.20E-02	2.20E-02	7.69E-02	7.70E-02	9.65E-05	0.13%
ANZ	2.87E-02	2.94E-02	6.73E-04	2.34%	1.26E-02	1.27E-02	2.93E-02	2.98E-02	5.25E-04	1.79%
ASI	9.29E-02	9.30E-02	6.31E-05	0.07%	2.82E-02	2.83E-02	9.43E-02	9.43E-02	6.50E-06	0.01%
CAN	1.04E-01	1.04E-01	5.76E-05	0.06%	3.29E-02	3.28E-02	1.07E-01	1.07E-01	-7.00E-05	-0.07%
CHN	1.06E-01	1.07E-01	9.82E-04	0.93%	3.23E-02	3.28E-02	1.08E-01	1.09E-01	9.75E-04	0.90%
EET	1.18E-01	1.18E-01	-4.51E-04	-0.38%	3.83E-02	3.80E-02	1.21E-01	1.21E-01	-2.35E-04	-0.19%
EUR	1.02E-01	1.01E-01	-1.61E-04	-0.16%	3.21E-02	3.19E-02	1.05E-01	1.04E-01	-2.15E-04	-0.21%
FSU	1.13E-01	1.13E-01	-3.62E-04	-0.32%	3.64E-02	3.61E-02	1.16E-01	1.15E-01	-6.35E-04	-0.55%
IDZ	7.69E-02	7.67E-02	-2.34E-04	-0.30%	2.45E-02	2.44E-02	7.65E-02	7.62E-02	-2.83E-04	-0.37%
IND	8.88E-02	8.92E-02	3.20E-04	0.36%	2.60E-02	2.62E-02	9.00E-02	9.00E-02	4.40E-05	0.05%
JPN	1.01E-01	1.02E-01	2.42E-04	0.24%	3.15E-02	3.16E-02	1.04E-01	1.04E-01	2.55E-04	0.24%
LAM	7.62E-02	7.62E-02	-1.72E-05	-0.02%	2.22E-02	2.22E-02	7.64E-02	7.65E-02	6.55E-05	0.09%
MES	1.10E-01	1.10E-01	1.81E-04	0.16%	3.47E-02	3.48E-02	1.11E-01	1.12E-01	1.13E-03	1.02%
MEX	9.07E-02	9.08E-02	9.78E-05	0.11%	2.80E-02	2.80E-02	9.07E-02	9.16E-02	8.89E-04	0.98%
ROW	1.18E-01	1.18E-01	-1.62E-04	-0.14%	3.77E-02	3.76E-02	1.20E-01	1.20E-01	-2.45E-04	-0.20%
USA	1.02E-01	1.02E-01	2.43E-04	0.24%	3.18E-02	3.19E-02	1.04E-01	1.05E-01	3.10E-04	0.30%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	5.69E-02	5.69E-02	-4.37E-06	-0.01%	1.08E-02	1.08E-02	5.54E-02	5.51E-02	-2.55E-04	-0.46%
ANZ	1.77E-02	1.83E-02	5.64E-04	3.18%	6.02E-03	6.06E-03	1.64E-02	1.70E-02	5.62E-04	3.43%
ASI	6.81E-02	6.81E-02	1.64E-05	0.02%	1.38E-02	1.39E-02	6.63E-02	6.60E-02	-2.71E-04	-0.41%
CAN	7.48E-02	7.50E-02	1.79E-04	0.24%	1.79E-02	1.80E-02	7.36E-02	7.40E-02	4.33E-04	0.59%
CHN	7.76E-02	7.81E-02	4.81E-04	0.62%	1.67E-02	1.70E-02	7.64E-02	7.68E-02	4.33E-04	0.57%
EET	8.45E-02	8.44E-02	-9.41E-05	-0.11%	2.03E-02	2.02E-02	8.29E-02	8.33E-02	3.65E-04	0.44%
EUR	7.33E-02	7.33E-02	5.85E-05	0.08%	1.74E-02	1.74E-02	7.21E-02	7.22E-02	1.56E-04	0.22%
FSU	8.09E-02	8.08E-02	-2.61E-05	-0.03%	1.91E-02	1.91E-02	7.94E-02	7.95E-02	7.90E-05	0.10%
IDZ	5.65E-02	5.64E-02	-1.19E-04	-0.21%	1.18E-02	1.17E-02	5.41E-02	5.42E-02	7.75E-05	0.14%
IND	6.60E-02	6.61E-02	1.06E-04	0.16%	1.25E-02	1.26E-02	6.38E-02	6.38E-02	4.85E-05	0.08%
JPN	7.37E-02	7.39E-02	2.16E-04	0.29%	1.70E-02	1.71E-02	7.30E-02	7.30E-02	3.65E-05	0.05%
LAM	5.67E-02	5.67E-02	-1.33E-05	-0.02%	1.03E-02	1.03E-02	5.43E-02	5.43E-02	3.95E-05	0.07%
MES	7.95E-02	7.96E-02	7.85E-05	0.10%	1.71E-02	1.72E-02	7.79E-02	7.80E-02	6.70E-05	0.09%
MEX	6.61E-02	6.62E-02	9.73E-05	0.15%	1.32E-02	1.33E-02	6.39E-02	6.40E-02	1.34E-04	0.21%
ROW	8.45E-02	8.44E-02	-2.10E-05	-0.02%	1.91E-02	1.92E-02	8.30E-02	8.29E-02	-9.05E-05	-0.11%
USA	7.38E-02	7.40E-02	2.05E-04	0.28%	1.71E-02	1.72E-02	7.28E-02	7.30E-02	1.52E-04	0.21%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.65E-02	4.65E-02	-1.25E-05	-0.03%	3.49E-03	3.46E-03	4.63E-02	4.64E-02	2.20E-05	0.05%
ANZ	1.20E-02	1.26E-02	5.43E-04	4.51%	1.64E-03	1.61E-03	1.19E-02	1.25E-02	5.39E-04	4.51%
ASI	5.45E-02	5.44E-02	-5.59E-05	-0.10%	4.37E-03	4.35E-03	5.41E-02	5.41E-02	5.40E-05	0.10%
CAN	5.71E-02	5.72E-02	7.50E-05	0.13%	9.08E-03	9.25E-03	6.04E-02	6.07E-02	2.45E-04	0.40%
CHN	6.10E-02	6.12E-02	1.96E-04	0.32%	7.43E-03	7.47E-03	6.33E-02	6.31E-02	-1.49E-04	-0.24%
EET	6.45E-02	6.45E-02	-7.77E-06	-0.01%	1.01E-02	1.01E-02	6.79E-02	6.78E-02	-1.49E-04	-0.22%
EUR	5.61E-02	5.61E-02	1.17E-06	0.00%	8.61E-03	8.67E-03	5.93E-02	5.93E-02	-3.65E-05	-0.06%
FSU	6.20E-02	6.20E-02	-1.32E-05	-0.02%	9.33E-03	9.39E-03	6.52E-02	6.50E-02	-1.90E-04	-0.29%
IDZ	4.71E-02	4.71E-02	3.75E-07	0.00%	5.50E-03	5.59E-03	4.56E-02	4.54E-02	-2.23E-04	-0.49%
IND	5.40E-02	5.41E-02	5.69E-05	0.11%	3.58E-03	3.64E-03	5.33E-02	5.36E-02	3.08E-04	0.58%
JPN	5.70E-02	5.71E-02	1.11E-04	0.20%	8.07E-03	8.04E-03	5.94E-02	5.90E-02	-4.36E-04	-0.73%
LAM	4.70E-02	4.70E-02	-4.43E-05	-0.09%	2.79E-03	2.78E-03	4.71E-02	4.71E-02	-1.85E-05	-0.04%
MES	6.27E-02	6.27E-02	3.26E-05	0.05%	7.26E-03	7.21E-03	6.43E-02	6.42E-02	-8.50E-06	-0.01%
MEX	5.31E-02	5.31E-02	9.50E-06	0.02%	3.94E-03	3.97E-03	5.27E-02	5.29E-02	1.67E-04	0.32%
ROW	6.56E-02	6.55E-02	-8.78E-05	-0.13%	8.75E-03	8.81E-03	6.81E-02	6.81E-02	-3.25E-05	-0.05%
USA	5.70E-02	5.70E-02	8.41E-05	0.15%	8.08E-03	8.10E-03	5.97E-02	5.93E-02	-3.69E-04	-0.62%

(2) Carbon Monoxide

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	6.01E-02	5.05E-02	-9.54E-03	-15.87%	1.97E-02	1.27E-02	6.63E-02	5.68E-02	-9.56E-03	-14.42%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	2.03E-29	0.00E+00	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	1.60E+00	1.55E+00	-5.75E-02	-3.58%	3.85E-01	3.40E-01	1.64E+00	1.59E+00	-5.48E-02	-3.33%
CAN	3.97E-01	3.84E-01	-1.21E-02	-3.06%	3.77E-02	3.49E-02	4.03E-01	3.87E-01	-1.59E-02	-3.95%
CHN	5.83E-01	5.15E-01	-6.86E-02	-11.76%	1.73E-01	1.36E-01	6.18E-01	5.41E-01	-7.75E-02	-12.53%
EET	3.20E-01	3.09E-01	-1.07E-02	-3.35%	6.10E-02	5.32E-02	3.19E-01	3.11E-01	-8.38E-03	-2.63%
EUR	2.50E-01	2.46E-01	-4.09E-03	-1.64%	2.81E-02	2.64E-02	2.58E-01	2.52E-01	-5.51E-03	-2.14%
FSU	5.09E-01	4.95E-01	-1.40E-02	-2.75%	6.88E-02	6.62E-02	5.22E-01	5.06E-01	-1.60E-02	-3.07%
IDZ	7.21E-01	7.02E-01	-1.91E-02	-2.65%	2.31E-01	2.20E-01	7.43E-01	7.25E-01	-1.75E-02	-2.36%
IND	4.72E-01	4.51E-01	-2.02E-02	-4.27%	1.48E-01	1.33E-01	4.85E-01	4.70E-01	-1.58E-02	-3.26%
JPN	6.70E-01	6.55E-01	-1.53E-02	-2.28%	1.11E-01	1.03E-01	6.93E-01	6.80E-01	-1.35E-02	-1.95%
LAM	1.02E+00	9.82E-01	-4.24E-02	-4.14%	3.90E-01	3.63E-01	1.09E+00	1.04E+00	-5.19E-02	-4.75%
MES	8.38E-01	7.84E-01	-5.37E-02	-6.41%	1.68E-01	1.43E-01	9.12E-01	8.37E-01	-7.57E-02	-8.30%
MEX	1.46E+00	1.40E+00	-5.27E-02	-3.62%	2.01E-01	1.79E-01	1.50E+00	1.44E+00	-6.35E-02	-4.22%
ROW	3.03E-01	2.98E-01	-4.49E-03	-1.48%	7.32E-02	7.08E-02	3.35E-01	3.29E-01	-5.98E-03	-1.79%
USA	3.82E-01	3.69E-01	-1.26E-02	-3.30%	3.48E-02	3.29E-02	3.90E-01	3.73E-01	-1.62E-02	-4.16%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.49E-02	4.28E-02	-2.06E-03	-4.59%	1.46E-02	0.012322	4.16E-02	4.16E-02	7.15E-05	0.17%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	3.75E-30	5.33E-23	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	1.27E+00	1.25E+00	-1.95E-02	-1.54%	2.04E-01	1.87E-01	1.24E+00	1.22E+00	-1.90E-02	-1.53%
CAN	3.86E-01	3.80E-01	-5.43E-03	-1.41%	3.88E-02	3.41E-02	3.89E-01	3.82E-01	-7.04E-03	-1.81%
CHN	4.35E-01	3.98E-01	-3.65E-02	-8.39%	1.08E-01	8.55E-02	4.26E-01	3.95E-01	-3.05E-02	-7.16%
EET	2.71E-01	2.67E-01	-4.11E-03	-1.51%	3.49E-02	3.27E-02	2.68E-01	2.64E-01	-4.09E-03	-1.52%
EUR	2.38E-01	2.36E-01	-2.15E-03	-0.90%	2.55E-02	2.44E-02	2.41E-01	2.39E-01	-2.17E-03	-0.90%
FSU	4.56E-01	4.43E-01	-1.26E-02	-2.76%	5.19E-02	4.87E-02	4.55E-01	4.37E-01	-1.77E-02	-3.90%
IDZ	5.33E-01	5.23E-01	-1.09E-02	-2.05%	1.41E-01	1.41E-01	5.24E-01	5.13E-01	-1.16E-02	-2.21%
IND	3.47E-01	3.40E-01	-6.68E-03	-1.93%	8.95E-02	8.63E-02	3.40E-01	3.34E-01	-6.49E-03	-1.91%
JPN	5.84E-01	5.77E-01	-6.76E-03	-1.16%	8.56E-02	8.12E-02	5.72E-01	5.71E-01	-1.59E-03	-0.28%
LAM	6.80E-01	6.62E-01	-1.78E-02	-2.61%	2.20E-01	2.06E-01	6.37E-01	6.32E-01	-5.22E-03	-0.82%
MES	7.25E-01	7.03E-01	-2.18E-02	-3.00%	1.72E-01	1.59E-01	7.60E-01	7.39E-01	-2.15E-02	-2.83%
MEX	1.33E+00	1.29E+00	-3.43E-02	-2.58%	1.99E-01	1.77E-01	1.34E+00	1.31E+00	-3.11E-02	-2.32%
ROW	2.52E-01	2.49E-01	-2.60E-03	-1.03%	6.75E-02	6.52E-02	2.45E-01	2.42E-01	-2.78E-03	-1.13%
USA	3.68E-01	3.64E-01	-4.55E-03	-1.23%	3.49E-02	3.18E-02	3.69E-01	3.66E-01	-3.38E-03	-0.92%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	3.16E-02	3.13E-02	-2.71E-04	-0.86%	5.99E-03	0.005981	3.19E-02	3.18E-02	-2.15E-05	-0.07%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	3.16E-30	7.38E-23	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	1.07E+00	1.07E+00	-3.15E-03	-0.29%	9.05E-02	9.05E-02	1.09E+00	1.09E+00	-2.45E-03	-0.23%
CAN	3.58E-01	3.57E-01	-9.93E-04	-0.28%	2.95E-02	2.61E-02	3.61E-01	3.60E-01	-1.01E-03	-0.28%
CHN	3.28E-01	3.14E-01	-1.41E-02	-4.30%	4.31E-02	3.62E-02	3.29E-01	3.13E-01	-1.56E-02	-4.76%
EET	2.44E-01	2.43E-01	-1.01E-03	-0.41%	2.09E-02	2.07E-02	2.46E-01	2.45E-01	-2.50E-04	-0.10%
EUR	2.24E-01	2.24E-01	-4.29E-04	-0.19%	2.03E-02	2.01E-02	2.28E-01	2.28E-01	-3.70E-04	-0.16%
FSU	4.09E-01	4.04E-01	-5.62E-03	-1.37%	2.84E-02	2.48E-02	4.05E-01	4.02E-01	-3.57E-03	-0.88%
IDZ	4.01E-01	3.89E-01	-1.23E-02	-3.07%	6.74E-02	6.60E-02	4.01E-01	3.86E-01	-1.48E-02	-3.70%
IND	2.56E-01	2.53E-01	-3.03E-03	-1.18%	3.55E-02	3.38E-02	2.53E-01	2.50E-01	-2.24E-03	-0.89%
JPN	5.07E-01	5.04E-01	-2.63E-03	-0.52%	3.87E-02	4.14E-02	5.06E-01	5.05E-01	-6.35E-04	-0.13%
LAM	4.65E-01	4.59E-01	-5.57E-03	-1.20%	6.44E-02	6.19E-02	4.67E-01	4.57E-01	-9.96E-03	-2.13%
MES	5.39E-01	5.31E-01	-8.09E-03	-1.50%	7.95E-02	7.66E-02	5.31E-01	5.26E-01	-5.54E-03	-1.04%
MEX	1.14E+00	1.14E+00	-5.00E-03	-0.44%	1.37E-01	1.35E-01	1.15E+00	1.15E+00	-2.95E-03	-0.26%
ROW	1.86E-01	1.85E-01	-4.20E-04	-0.23%	2.83E-02	2.80E-02	1.85E-01	1.87E-01	2.23E-03	1.20%
USA	3.43E-01	3.42E-01	-8.02E-04	-0.23%	2.49E-02	2.46E-02	3.47E-01	3.47E-01	5.15E-04	0.15%

(3) Nitrogen Dioxide

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	7.43E-03	6.74E-03	-6.96E-04	-9.37%	3.04E-03	0.0024	8.03E-03	7.64E-03	-3.92E-04	-4.87%
ANZ	7.38E-03	5.70E-03	-1.69E-03	-22.83%	7.41E-03	5.98E-03	5.79E-03	4.26E-03	-1.53E-03	-26.42%
ASI	8.65E-02	8.34E-02	-3.11E-03	-3.60%	2.16E-02	1.93E-02	8.86E-02	8.56E-02	-3.09E-03	-3.49%
CAN	1.89E-02	1.81E-02	-8.09E-04	-4.28%	4.86E-03	4.24E-03	1.91E-02	1.83E-02	-7.64E-04	-4.00%
CHN	5.40E-02	4.85E-02	-5.51E-03	-10.20%	1.95E-02	1.65E-02	5.63E-02	5.03E-02	-6.01E-03	-10.67%
EET	2.08E-02	2.04E-02	-3.26E-04	-1.57%	4.31E-03	4.11E-03	2.11E-02	2.09E-02	-2.46E-04	-1.17%
EUR	6.08E-03	5.89E-03	-1.91E-04	-3.15%	3.42E-03	3.26E-03	5.49E-03	5.32E-03	-1.71E-04	-3.11%
FSU	3.07E-02	3.02E-02	-4.94E-04	-1.61%	5.00E-03	5.12E-03	3.18E-02	3.12E-02	-5.57E-04	-1.75%
IDZ	3.91E-02	3.74E-02	-1.61E-03	-4.12%	1.29E-02	1.21E-02	3.96E-02	3.83E-02	-1.36E-03	-3.43%
IND	3.83E-02	3.68E-02	-1.53E-03	-4.01%	1.37E-02	1.25E-02	3.87E-02	3.77E-02	-1.08E-03	-2.79%
JPN	4.59E-02	4.51E-02	-8.31E-04	-1.81%	1.42E-02	1.37E-02	4.89E-02	4.76E-02	-1.36E-03	-2.78%
LAM	5.90E-02	5.66E-02	-2.37E-03	-4.02%	2.13E-02	1.98E-02	6.24E-02	5.96E-02	-2.78E-03	-4.45%
MES	4.96E-02	4.68E-02	-2.84E-03	-5.73%	1.02E-02	8.72E-03	5.37E-02	5.01E-02	-3.62E-03	-6.74%
MEX	7.99E-02	7.70E-02	-2.84E-03	-3.56%	1.24E-02	1.13E-02	8.31E-02	7.94E-02	-3.72E-03	-4.48%
ROW	2.16E-02	2.15E-02	-1.32E-04	-0.61%	4.91E-03	4.85E-03	2.34E-02	2.30E-02	-3.89E-04	-1.66%
USA	1.79E-02	1.72E-02	-7.48E-04	-4.18%	5.04E-03	4.54E-03	1.79E-02	1.70E-02	-9.75E-04	-5.43%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.88E-03	4.78E-03	-9.80E-05	-2.01%	1.99E-03	0.001848	4.31E-03	4.31E-03	4.80E-06	0.11%
ANZ	4.28E-03	3.89E-03	-3.87E-04	-9.06%	4.93E-03	4.49E-03	2.47E-03	1.94E-03	-5.26E-04	-21.28%
ASI	6.76E-02	6.64E-02	-1.20E-03	-1.78%	1.14E-02	1.05E-02	6.62E-02	6.50E-02	-1.17E-03	-1.76%
CAN	1.52E-02	1.49E-02	-2.59E-04	-1.70%	2.90E-03	2.65E-03	1.49E-02	1.48E-02	-1.37E-04	-0.92%
CHN	3.71E-02	3.43E-02	-2.84E-03	-7.66%	1.12E-02	9.34E-03	3.61E-02	3.39E-02	-2.17E-03	-6.01%
EET	1.72E-02	1.70E-02	-1.41E-04	-0.82%	2.67E-03	2.58E-03	1.72E-02	1.70E-02	-1.69E-04	-0.98%
EUR	3.47E-03	3.40E-03	-6.83E-05	-1.97%	1.44E-03	1.40E-03	3.07E-03	3.05E-03	-1.74E-05	-0.57%
FSU	2.67E-02	2.61E-02	-6.11E-04	-2.29%	3.68E-03	3.52E-03	2.68E-02	2.57E-02	-1.13E-03	-4.22%
IDZ	2.87E-02	2.77E-02	-9.89E-04	-3.44%	7.44E-03	7.49E-03	2.81E-02	2.67E-02	-1.39E-03	-4.93%
IND	2.66E-02	2.61E-02	-4.64E-04	-1.75%	7.34E-03	7.09E-03	2.59E-02	2.54E-02	-4.53E-04	-1.75%
JPN	3.37E-02	3.33E-02	-3.67E-04	-1.09%	8.58E-03	8.37E-03	3.19E-02	3.21E-02	2.07E-04	0.65%
LAM	4.02E-02	3.92E-02	-1.06E-03	-2.64%	1.18E-02	1.11E-02	3.79E-02	3.75E-02	-4.36E-04	-1.15%
MES	4.23E-02	4.11E-02	-1.19E-03	-2.82%	9.73E-03	9.03E-03	4.38E-02	4.30E-02	-7.78E-04	-1.78%
MEX	7.13E-02	6.93E-02	-1.95E-03	-2.73%	1.14E-02	1.03E-02	7.17E-02	7.02E-02	-1.51E-03	-2.10%
ROW	1.79E-02	1.78E-02	-8.92E-05	-0.50%	4.31E-03	4.18E-03	1.78E-02	1.76E-02	-1.71E-04	-0.96%
USA	1.41E-02	1.39E-02	-2.03E-04	-1.44%	3.07E-03	2.88E-03	1.36E-02	1.35E-02	-5.55E-05	-0.41%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	2.97E-03	2.99E-03	2.07E-05	0.70%	6.00E-04	0.000588	3.04E-03	3.04E-03	-8.25E-06	-0.27%
ANZ	2.34E-03	2.23E-03	-1.08E-04	-4.61%	2.84E-03	2.73E-03	4.43E-04	4.90E-04	4.70E-05	10.61%
ASI	5.67E-02	5.64E-02	-3.08E-04	-0.54%	4.94E-03	4.92E-03	5.75E-02	5.70E-02	-5.54E-04	-0.96%
CAN	1.26E-02	1.25E-02	-3.42E-05	-0.27%	1.51E-03	1.40E-03	1.25E-02	1.24E-02	-1.05E-04	-0.84%
CHN	2.59E-02	2.49E-02	-1.02E-03	-3.93%	4.19E-03	3.53E-03	2.60E-02	2.49E-02	-1.10E-03	-4.22%
EET	1.48E-02	1.48E-02	1.60E-06	0.01%	1.83E-03	1.86E-03	1.51E-02	1.50E-02	-3.55E-05	-0.24%
EUR	2.29E-03	2.26E-03	-3.72E-05	-1.62%	4.84E-04	4.75E-04	2.27E-03	2.19E-03	-7.36E-05	-3.25%
FSU	2.32E-02	2.29E-02	-2.61E-04	-1.12%	1.99E-03	1.77E-03	2.32E-02	2.30E-02	-2.61E-04	-1.12%
IDZ	2.21E-02	2.10E-02	-1.13E-03	-5.09%	3.61E-03	3.51E-03	2.17E-02	2.09E-02	-7.68E-04	-3.55%
IND	1.91E-02	1.89E-02	-1.81E-04	-0.95%	2.54E-03	2.38E-03	1.90E-02	1.86E-02	-3.55E-04	-1.87%
JPN	2.58E-02	2.56E-02	-1.60E-04	-0.62%	2.82E-03	3.09E-03	2.57E-02	2.56E-02	-1.44E-04	-0.56%
LAM	2.86E-02	2.83E-02	-3.81E-04	-1.33%	3.37E-03	3.21E-03	2.86E-02	2.80E-02	-5.96E-04	-2.08%
MES	3.18E-02	3.14E-02	-4.72E-04	-1.48%	4.51E-03	4.38E-03	3.15E-02	3.11E-02	-4.33E-04	-1.37%
MEX	6.07E-02	6.03E-02	-3.75E-04	-0.62%	7.46E-03	7.41E-03	6.08E-02	6.06E-02	-2.38E-04	-0.39%
ROW	1.37E-02	1.37E-02	2.55E-05	0.19%	2.31E-03	2.28E-03	1.38E-02	1.39E-02	8.20E-05	0.59%
USA	1.14E-02	1.13E-02	-1.73E-05	-0.15%	1.19E-03	1.16E-03	1.13E-02	1.11E-02	-1.27E-04	-1.12%

(4) Sulfur Dioxide

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	2.83E-04	2.25E-04	-5.79E-05	-20.47%	1.47E-04	0.00014015	2.56E-04	1.71E-04	-8.56E-05	-33.42%
ANZ	8.45E-03	1.00E-15	-8.45E-03	-100.00%	2.35E-03	0.00E+00	8.29E-03	1.00E-15	-8.29E-03	-100.00%
ASI	8.64E-04	7.89E-04	-7.51E-05	-8.68%	3.76E-04	3.80E-04	8.43E-04	7.39E-04	-1.04E-04	-12.29%
CAN	2.13E-03	2.67E-04	-1.86E-03	-87.47%	1.66E-03	1.70E-04	1.71E-03	2.08E-04	-1.50E-03	-87.78%
CHN	6.53E-04	3.94E-04	-2.59E-04	-39.69%	2.70E-04	2.80E-04	6.98E-04	3.24E-04	-3.74E-04	-53.55%
EET	6.06E-04	5.70E-04	-3.59E-05	-5.93%	2.95E-04	3.06E-04	5.17E-04	4.67E-04	-5.04E-05	-9.75%
EUR	1.87E-03	2.56E-04	-1.61E-03	-86.31%	1.46E-03	1.64E-04	1.46E-03	1.96E-04	-1.27E-03	-86.59%
FSU	5.17E-04	4.94E-04	-2.35E-05	-4.55%	2.86E-04	2.91E-04	4.33E-04	4.05E-04	-2.79E-05	-6.43%
IDZ	2.35E-04	2.11E-04	-2.36E-05	-10.07%	2.01E-04	1.85E-04	2.00E-04	1.72E-04	-2.76E-05	-13.82%
IND	1.27E-03	1.06E-03	-2.11E-04	-16.57%	5.06E-04	5.34E-04	1.28E-03	1.07E-03	-2.08E-04	-16.23%
JPN	1.85E-03	1.48E-04	-1.71E-03	-91.99%	9.99E-04	6.31E-05	1.74E-03	1.45E-04	-1.59E-03	-91.66%
LAM	5.70E-05	4.69E-05	-1.01E-05	-17.71%	6.35E-05	5.92E-05	2.18E-05	1.69E-05	-4.93E-06	-22.54%
MES	3.50E-04	3.34E-04	-1.57E-05	-4.50%	1.27E-04	1.23E-04	3.13E-04	2.92E-04	-2.06E-05	-6.58%
MEX	5.35E-04	5.05E-04	-3.04E-05	-5.67%	2.73E-04	2.71E-04	5.07E-04	4.54E-04	-5.37E-05	-10.58%
ROW	5.10E-04	4.55E-04	-5.47E-05	-10.73%	1.87E-04	1.84E-04	4.53E-04	3.98E-04	-5.54E-05	-12.23%
USA	1.89E-03	1.37E-04	-1.75E-03	-92.75%	9.80E-04	6.35E-05	1.77E-03	1.30E-04	-1.64E-03	-92.66%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.06E-04	3.19E-04	-8.75E-05	-21.54%	1.03E-04	0.00014219	3.97E-04	2.96E-04	-1.01E-04	-25.38%
ANZ	7.35E-03	1.00E-15	-7.35E-03	-100.00%	1.83E-03	5.33E-23	7.39E-03	1.00E-15	-7.39E-03	-100.00%
ASI	1.15E-03	1.07E-03	-7.87E-05	-6.86%	2.77E-04	3.05E-04	1.09E-03	1.01E-03	-8.52E-05	-7.79%
CAN	1.49E-03	2.53E-04	-1.24E-03	-83.03%	1.19E-03	1.93E-04	1.22E-03	1.78E-04	-1.05E-03	-85.44%
CHN	8.69E-04	6.29E-04	-2.40E-04	-27.58%	1.47E-04	1.96E-04	8.36E-04	6.22E-04	-2.14E-04	-25.56%
EET	5.83E-04	5.40E-04	-4.31E-05	-7.40%	3.24E-04	3.24E-04	4.89E-04	4.40E-04	-4.80E-05	-9.83%
EUR	1.23E-03	2.52E-04	-9.77E-04	-79.51%	9.32E-04	1.85E-04	9.98E-04	1.81E-04	-8.17E-04	-81.86%
FSU	4.35E-04	4.04E-04	-3.05E-05	-7.03%	2.77E-04	2.72E-04	3.23E-04	2.93E-04	-3.03E-05	-9.39%
IDZ	4.00E-04	3.61E-04	-3.93E-05	-9.83%	1.47E-04	1.40E-04	3.75E-04	3.36E-04	-3.97E-05	-10.57%
IND	1.71E-03	1.53E-03	-1.80E-04	-10.56%	2.76E-04	2.83E-04	1.66E-03	1.49E-03	-1.68E-04	-10.13%
JPN	1.30E-03	1.44E-04	-1.16E-03	-88.98%	7.06E-04	5.98E-05	1.19E-03	1.33E-04	-1.06E-03	-88.86%
LAM	1.02E-04	8.46E-05	-1.69E-05	-16.69%	6.37E-05	6.44E-05	9.46E-05	7.44E-05	-2.02E-05	-21.36%
MES	4.02E-04	3.83E-04	-1.90E-05	-4.73%	1.35E-04	1.34E-04	3.67E-04	3.49E-04	-1.78E-05	-4.86%
MEX	7.66E-04	7.29E-04	-3.66E-05	-4.78%	1.77E-04	1.93E-04	7.44E-04	7.10E-04	-3.41E-05	-4.59%
ROW	5.68E-04	5.24E-04	-4.41E-05	-7.76%	2.01E-04	1.97E-04	5.08E-04	4.57E-04	-5.12E-05	-10.08%
USA	1.34E-03	1.17E-04	-1.22E-03	-91.23%	7.10E-04	6.02E-05	1.20E-03	1.07E-04	-1.09E-03	-91.05%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.95E-04	4.62E-04	-3.28E-05	-6.64%	8.96E-05	9.6496E-05	4.73E-04	4.32E-04	-4.03E-05	-8.53%
ANZ	6.75E-03	1.00E-15	-6.75E-03	-100.00%	1.55E-03	7.38E-23	6.80E-03	1.00E-15	-6.80E-03	-100.00%
ASI	1.42E-03	1.38E-03	-4.09E-05	-2.89%	2.04E-04	2.11E-04	1.37E-03	1.35E-03	-1.60E-05	-1.17%
CAN	1.14E-03	2.47E-04	-8.94E-04	-78.38%	9.25E-04	2.11E-04	9.37E-04	1.76E-04	-7.61E-04	-81.22%
CHN	9.13E-04	7.88E-04	-1.25E-04	-13.73%	1.50E-04	1.45E-04	8.81E-04	7.72E-04	-1.09E-04	-12.40%
EET	6.10E-04	5.84E-04	-2.62E-05	-4.30%	3.43E-04	3.40E-04	5.05E-04	4.59E-04	-4.65E-05	-9.21%
EUR	9.13E-04	2.49E-04	-6.64E-04	-72.73%	6.99E-04	1.96E-04	7.57E-04	1.84E-04	-5.72E-04	-75.66%
FSU	4.06E-04	3.87E-04	-1.90E-05	-4.69%	2.68E-04	2.64E-04	3.09E-04	2.78E-04	-3.10E-05	-10.04%
IDZ	5.43E-04	4.93E-04	-4.99E-05	-9.20%	1.08E-04	1.09E-04	5.35E-04	4.70E-04	-6.49E-05	-12.15%
IND	1.81E-03	1.69E-03	-1.16E-04	-6.41%	2.45E-04	2.42E-04	1.75E-03	1.63E-03	-1.17E-04	-6.68%
JPN	1.02E-03	1.56E-04	-8.60E-04	-84.65%	6.26E-04	7.52E-05	8.63E-04	1.53E-04	-7.10E-04	-82.24%
LAM	1.60E-04	1.46E-04	-1.38E-05	-8.64%	5.16E-05	5.20E-05	1.56E-04	1.40E-04	-1.64E-05	-10.51%
MES	3.80E-04	3.67E-04	-1.32E-05	-3.47%	1.39E-04	1.38E-04	3.41E-04	3.38E-04	-3.18E-06	-0.93%
MEX	9.33E-04	9.14E-04	-1.90E-05	-2.03%	1.17E-04	1.30E-04	9.12E-04	9.05E-04	-7.29E-06	-0.80%
ROW	5.68E-04	5.55E-04	-1.25E-05	-2.20%	2.09E-04	2.08E-04	5.06E-04	4.95E-04	-1.10E-05	-2.18%
USA	1.02E-03	1.17E-04	-9.03E-04	-88.51%	6.01E-04	7.29E-05	8.78E-04	1.15E-04	-7.63E-04	-86.87%

(5) Formaldehyde

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	2.62E-04	2.19E-04	-4.35E-05	-16.60%	1.05E-04	7.46015E-05	2.90E-04	2.43E-04	-4.70E-05	-16.22%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	2.03E-29	0.00E+00	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	1.36E-02	1.27E-02	-8.74E-04	-6.43%	3.75E-03	3.09E-03	1.37E-02	1.31E-02	-6.24E-04	-4.56%
CAN	1.97E-04	1.89E-04	-7.94E-06	-4.03%	5.06E-05	4.47E-05	1.99E-04	1.90E-04	-9.65E-06	-4.84%
CHN	1.32E-03	1.16E-03	-1.66E-04	-12.54%	4.47E-04	3.40E-04	1.38E-03	1.19E-03	-1.84E-04	-13.36%
EET	1.72E-03	1.64E-03	-8.47E-05	-4.91%	4.66E-04	3.75E-04	1.67E-03	1.63E-03	-4.84E-05	-2.89%
EUR	4.94E-05	5.18E-05	2.40E-06	4.85%	3.01E-05	3.33E-05	3.97E-05	4.12E-05	1.48E-06	3.73%
FSU	3.31E-03	3.18E-03	-1.30E-04	-3.94%	5.53E-04	4.93E-04	3.32E-03	3.25E-03	-6.70E-05	-2.02%
IDZ	5.22E-03	4.66E-03	-5.61E-04	-10.75%	2.01E-03	1.75E-03	5.13E-03	4.70E-03	-4.34E-04	-8.45%
IND	4.15E-03	3.85E-03	-2.92E-04	-7.05%	1.46E-03	1.23E-03	4.20E-03	4.01E-03	-1.86E-04	-4.42%
JPN	6.80E-04	6.57E-04	-2.28E-05	-3.35%	2.15E-04	1.93E-04	6.86E-04	6.69E-04	-1.66E-05	-2.41%
LAM	8.75E-03	8.12E-03	-6.27E-04	-7.17%	3.66E-03	3.24E-03	9.25E-03	8.61E-03	-6.37E-04	-6.89%
MES	6.41E-03	5.81E-03	-5.98E-04	-9.34%	1.51E-03	1.22E-03	6.89E-03	6.16E-03	-7.28E-04	-10.57%
MEX	1.12E-02	1.05E-02	-6.78E-04	-6.05%	1.92E-03	1.61E-03	1.14E-02	1.07E-02	-7.33E-04	-6.42%
ROW	1.81E-03	1.74E-03	-7.34E-05	-4.05%	5.96E-04	5.44E-04	1.97E-03	1.89E-03	-7.40E-05	-3.76%
USA	1.99E-04	1.96E-04	-2.97E-06	-1.49%	4.13E-05	4.14E-05	2.00E-04	1.93E-04	-6.82E-06	-3.41%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.85E-04	1.72E-04	-1.24E-05	-6.69%	8.82E-05	7.71292E-05	1.73E-04	1.69E-04	-4.54E-06	-2.62%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	3.75E-30	5.33E-23	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	1.04E-02	1.00E-02	-3.19E-04	-3.08%	1.92E-03	1.70E-03	1.02E-02	9.87E-03	-3.04E-04	-2.99%
CAN	1.75E-04	1.74E-04	-6.81E-07	-0.39%	4.96E-05	4.55E-05	1.72E-04	1.75E-04	3.31E-06	1.93%
CHN	9.45E-04	8.79E-04	-6.57E-05	-6.96%	2.58E-04	2.10E-04	9.25E-04	8.58E-04	-6.62E-05	-7.16%
EET	1.37E-03	1.35E-03	-2.43E-05	-1.78%	2.30E-04	2.15E-04	1.34E-03	1.32E-03	-1.52E-05	-1.14%
EUR	4.08E-05	4.30E-05	2.18E-06	5.33%	2.57E-05	2.93E-05	3.24E-05	3.25E-05	2.05E-08	0.06%
FSU	2.90E-03	2.80E-03	-1.05E-04	-3.63%	3.83E-04	3.55E-04	2.87E-03	2.73E-03	-1.48E-04	-5.16%
IDZ	3.71E-03	3.37E-03	-3.35E-04	-9.05%	1.18E-03	1.14E-03	3.61E-03	3.23E-03	-3.84E-04	-10.62%
IND	2.93E-03	2.84E-03	-9.00E-05	-3.07%	8.32E-04	7.78E-04	2.87E-03	2.74E-03	-1.27E-04	-4.43%
JPN	5.21E-04	5.18E-04	-3.07E-06	-0.59%	1.47E-04	1.38E-04	4.94E-04	4.89E-04	-4.85E-06	-0.98%
LAM	5.53E-03	5.28E-03	-2.47E-04	-4.48%	1.98E-03	1.81E-03	5.08E-03	5.01E-03	-6.91E-05	-1.36%
MES	5.40E-03	5.15E-03	-2.46E-04	-4.56%	1.49E-03	1.34E-03	5.61E-03	5.36E-03	-2.56E-04	-4.56%
MEX	1.00E-02	9.65E-03	-3.91E-04	-3.89%	1.78E-03	1.57E-03	1.01E-02	9.74E-03	-4.04E-04	-3.99%
ROW	1.40E-03	1.37E-03	-3.00E-05	-2.15%	5.26E-04	4.96E-04	1.33E-03	1.29E-03	-3.83E-05	-2.89%
USA	1.77E-04	1.81E-04	3.72E-06	2.10%	3.92E-05	3.98E-05	1.73E-04	1.74E-04	1.46E-06	0.84%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	9.58E-05	9.35E-05	-2.34E-06	-2.44%	3.25E-05	2.97323E-05	8.85E-05	8.98E-05	1.28E-06	1.44%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	3.16E-30	7.38E-23	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	8.64E-03	8.53E-03	-1.11E-04	-1.28%	9.11E-04	8.98E-04	8.74E-03	8.57E-03	-1.73E-04	-1.98%
CAN	1.48E-04	1.49E-04	1.21E-06	0.82%	3.95E-05	3.54E-05	1.41E-04	1.47E-04	5.63E-06	3.98%
CHN	6.98E-04	6.88E-04	-9.23E-06	-1.32%	1.01E-04	1.03E-04	6.89E-04	6.82E-04	-6.84E-06	-0.99%
EET	1.21E-03	1.21E-03	2.16E-06	0.18%	1.26E-04	1.43E-04	1.20E-03	1.20E-03	-2.70E-06	-0.22%
EUR	3.85E-05	3.89E-05	4.16E-07	1.08%	2.46E-05	2.80E-05	3.10E-05	2.72E-05	-3.80E-06	-12.23%
FSU	2.57E-03	2.53E-03	-4.25E-05	-1.65%	1.87E-04	1.82E-04	2.57E-03	2.52E-03	-5.32E-05	-2.07%
IDZ	2.73E-03	2.42E-03	-3.15E-04	-11.54%	6.43E-04	6.07E-04	2.68E-03	2.36E-03	-3.22E-04	-11.99%
IND	2.09E-03	2.06E-03	-3.36E-05	-1.61%	3.24E-04	2.92E-04	2.06E-03	2.03E-03	-3.03E-05	-1.47%
JPN	4.05E-04	4.07E-04	2.64E-06	0.65%	6.51E-05	6.76E-05	3.92E-04	4.01E-04	8.34E-06	2.13%
LAM	3.61E-03	3.51E-03	-9.29E-05	-2.58%	5.82E-04	5.46E-04	3.63E-03	3.50E-03	-1.33E-04	-3.65%
MES	3.83E-03	3.72E-03	-1.04E-04	-2.71%	6.82E-04	6.52E-04	3.70E-03	3.66E-03	-3.47E-05	-0.94%
MEX	8.54E-03	8.45E-03	-8.30E-05	-0.97%	1.29E-03	1.26E-03	8.38E-03	8.49E-03	1.12E-04	1.33%
ROW	8.78E-04	8.73E-04	-4.39E-06	-0.50%	1.86E-04	1.78E-04	8.52E-04	8.52E-04	-4.50E-07	-0.05%
USA	1.52E-04	1.58E-04	5.34E-06	3.50%	3.08E-05	3.41E-05	1.45E-04	1.50E-04	4.64E-06	3.20%

(6) Sulfate Aerosols

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.07E+01	1.01E+01	-6.01E-01	-5.60%	1.64E+00	1.4910548	1.10E+01	1.03E+01	-6.76E-01	-6.14%
ANZ	3.13E+00	5.08E-01	-2.63E+00	-83.78%	1.13E+00	4.52E-01	3.00E+00	3.28E-01	-2.67E+00	-89.05%
ASI	1.52E+01	1.50E+01	-2.26E-01	-1.49%	1.56E+00	1.40E+00	1.54E+01	1.51E+01	-2.29E-01	-1.49%
CAN	6.29E+01	6.52E+01	2.32E+00	3.68%	4.45E+01	4.56E+01	4.61E+01	4.72E+01	1.06E+00	2.29%
CHN	2.31E+01	2.24E+01	-7.22E-01	-3.12%	3.00E+00	3.03E+00	2.34E+01	2.28E+01	-5.97E-01	-2.55%
EET	1.80E+01	1.86E+01	5.22E-01	2.89%	3.35E+00	3.56E+00	1.76E+01	1.79E+01	3.12E-01	1.78%
EUR	5.99E+01	6.27E+01	2.83E+00	4.72%	4.37E+01	4.51E+01	4.29E+01	4.50E+01	2.12E+00	4.96%
FSU	1.63E+01	1.68E+01	5.28E-01	3.24%	2.94E+00	3.13E+00	1.59E+01	1.62E+01	3.82E-01	2.41%
IDZ	1.23E+01	1.13E+01	-9.74E-01	-7.92%	2.69E+00	2.61E+00	1.28E+01	1.17E+01	-1.12E+00	-8.75%
IND	1.33E+01	1.23E+01	-9.52E-01	-7.18%	1.59E+00	1.73E+00	1.33E+01	1.24E+01	-8.97E-01	-6.75%
JPN	2.65E+01	2.67E+01	2.64E-01	1.00%	1.45E+01	1.40E+01	2.31E+01	2.33E+01	1.92E-01	0.83%
LAM	9.16E+00	8.89E+00	-2.71E-01	-2.96%	8.35E-01	7.85E-01	9.29E+00	8.99E+00	-3.05E-01	-3.28%
MES	1.82E+01	1.82E+01	-3.94E-03	-0.02%	2.03E+00	1.93E+00	1.84E+01	1.84E+01	2.85E-02	0.16%
MEX	1.49E+01	1.48E+01	-1.49E-01	-1.00%	1.49E+00	1.51E+00	1.48E+01	1.47E+01	-1.48E-01	-0.99%
ROW	1.89E+01	1.88E+01	-1.29E-01	-0.68%	2.44E+00	2.31E+00	1.90E+01	1.89E+01	-1.76E-01	-0.92%
USA	2.97E+01	3.04E+01	7.04E-01	2.37%	1.59E+01	1.55E+01	2.49E+01	2.60E+01	1.02E+00	4.11%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.18E+01	1.11E+01	-7.10E-01	-6.02%	9.11E-01	0.9078736	1.18E+01	1.10E+01	-7.67E-01	-6.51%
ANZ	2.75E+00	5.13E-01	-2.24E+00	-81.35%	1.00E+00	4.53E-01	2.60E+00	3.42E-01	-2.26E+00	-86.87%
ASI	1.58E+01	1.54E+01	-4.10E-01	-2.59%	1.21E+00	1.15E+00	1.58E+01	1.54E+01	-3.71E-01	-2.35%
CAN	7.46E+01	7.46E+01	3.05E-02	0.04%	5.19E+01	5.27E+01	5.29E+01	5.18E+01	-1.15E+00	-2.17%
CHN	2.15E+01	2.04E+01	-1.08E+00	-5.04%	2.87E+00	2.70E+00	2.18E+01	2.06E+01	-1.19E+00	-5.47%
EET	1.88E+01	1.86E+01	-1.41E-01	-0.75%	3.98E+00	4.14E+00	1.82E+01	1.78E+01	-4.66E-01	-2.56%
EUR	7.06E+01	7.08E+01	2.20E-01	0.31%	5.07E+01	5.13E+01	4.94E+01	4.92E+01	-1.77E-01	-0.36%
FSU	1.67E+01	1.66E+01	-1.06E-01	-0.63%	3.51E+00	3.64E+00	1.61E+01	1.58E+01	-3.09E-01	-1.92%
IDZ	1.20E+01	1.10E+01	-1.06E+00	-8.79%	3.35E+00	3.16E+00	1.30E+01	1.17E+01	-1.34E+00	-10.24%
IND	1.42E+01	1.34E+01	-7.86E-01	-5.52%	1.19E+00	1.23E+00	1.43E+01	1.35E+01	-8.07E-01	-5.63%
JPN	3.38E+01	3.32E+01	-5.65E-01	-1.67%	1.51E+01	1.51E+01	3.07E+01	2.97E+01	-9.81E-01	-3.19%
LAM	8.95E+00	8.69E+00	-2.57E-01	-2.87%	9.36E-01	8.66E-01	9.11E+00	8.83E+00	-2.78E-01	-3.05%
MES	1.86E+01	1.83E+01	-2.77E-01	-1.49%	2.04E+00	1.98E+00	1.89E+01	1.85E+01	-3.69E-01	-1.95%
MEX	1.52E+01	1.48E+01	-3.22E-01	-2.13%	1.38E+00	1.47E+00	1.50E+01	1.47E+01	-2.81E-01	-1.87%
ROW	1.96E+01	1.93E+01	-3.21E-01	-1.64%	2.46E+00	2.45E+00	1.97E+01	1.94E+01	-2.95E-01	-1.49%
USA	3.65E+01	3.63E+01	-2.36E-01	-0.65%	1.74E+01	1.73E+01	3.37E+01	3.31E+01	-5.54E-01	-1.64%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.18E+01	1.14E+01	-3.30E-01	-2.81%	1.03E+00	0.9918658	1.17E+01	1.13E+01	-3.87E-01	-3.31%
ANZ	2.44E+00	4.40E-01	-2.00E+00	-81.94%	8.93E-01	4.41E-01	2.30E+00	2.69E-01	-2.03E+00	-88.31%
ASI	1.58E+01	1.55E+01	-2.54E-01	-1.61%	1.42E+00	1.35E+00	1.59E+01	1.55E+01	-3.43E-01	-2.17%
CAN	7.84E+01	7.81E+01	-2.82E-01	-0.36%	5.64E+01	5.70E+01	5.51E+01	5.64E+01	1.38E+00	2.50%
CHN	2.01E+01	1.93E+01	-7.45E-01	-3.71%	3.14E+00	3.21E+00	2.03E+01	1.96E+01	-6.81E-01	-3.35%
EET	1.81E+01	1.78E+01	-2.14E-01	-1.19%	4.84E+00	4.85E+00	1.75E+01	1.72E+01	-2.94E-01	-1.69%
EUR	7.21E+01	7.17E+01	-3.60E-01	-0.50%	5.26E+01	5.27E+01	5.11E+01	5.09E+01	-2.06E-01	-0.40%
FSU	1.58E+01	1.56E+01	-1.53E-01	-0.97%	4.12E+00	4.14E+00	1.52E+01	1.51E+01	-5.55E-02	-0.37%
IDZ	9.10E+00	8.17E+00	-9.27E-01	-10.19%	3.34E+00	2.93E+00	8.45E+00	7.81E+00	-6.37E-01	-7.54%
IND	1.46E+01	1.40E+01	-5.88E-01	-4.04%	1.13E+00	1.21E+00	1.46E+01	1.40E+01	-6.57E-01	-4.48%
JPN	3.88E+01	3.82E+01	-6.02E-01	-1.55%	1.95E+01	1.94E+01	3.67E+01	3.74E+01	7.06E-01	1.93%
LAM	8.12E+00	7.94E+00	-1.74E-01	-2.14%	7.89E-01	7.35E-01	8.22E+00	7.98E+00	-2.41E-01	-2.93%
MES	1.81E+01	1.78E+01	-3.09E-01	-1.71%	2.69E+00	2.60E+00	1.84E+01	1.81E+01	-3.08E-01	-1.68%
MEX	1.52E+01	1.49E+01	-2.79E-01	-1.83%	1.58E+00	1.63E+00	1.51E+01	1.48E+01	-3.00E-01	-1.99%
ROW	1.91E+01	1.90E+01	-1.31E-01	-0.68%	3.28E+00	3.35E+00	1.93E+01	1.90E+01	-2.44E-01	-1.27%
USA	4.13E+01	4.11E+01	-1.81E-01	-0.44%	2.14E+01	2.14E+01	3.96E+01	4.00E+01	4.22E-01	1.07%

(7) Black Carbon

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.15E+02	3.62E+02	-5.25E+01	-12.67%	7.49E+01	91.11223204	4.14E+02	3.64E+02	-4.99E+01	-12.05%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	2.03E-29	0.00E+00	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	7.71E+02	6.54E+02	-1.17E+02	-15.19%	1.52E+02	1.14E+02	7.38E+02	6.41E+02	-9.74E+01	-13.19%
CAN	1.45E+03	1.54E+03	8.92E+01	6.17%	8.56E+02	9.21E+02	1.06E+03	1.07E+03	4.90E+00	0.46%
CHN	8.31E+02	7.17E+02	-1.14E+02	-13.75%	2.11E+02	1.79E+02	8.07E+02	6.90E+02	-1.18E+02	-14.59%
EET	4.67E+02	4.56E+02	-1.13E+01	-2.41%	1.16E+02	1.02E+02	4.52E+02	4.49E+02	-3.10E+00	-0.69%
EUR	1.43E+03	1.53E+03	9.92E+01	6.93%	8.78E+02	9.49E+02	1.04E+03	1.05E+03	6.35E+00	0.61%
FSU	4.92E+02	4.84E+02	-8.26E+00	-1.68%	1.08E+02	9.45E+01	4.79E+02	4.76E+02	-3.01E+00	-0.63%
IDZ	8.58E+02	6.31E+02	-2.28E+02	-26.54%	1.33E+02	1.04E+02	8.49E+02	6.26E+02	-2.23E+02	-26.30%
IND	1.02E+03	7.99E+02	-2.20E+02	-21.60%	2.38E+02	3.13E+02	9.71E+02	8.07E+02	-1.63E+02	-16.83%
JPN	8.76E+02	8.65E+02	-1.14E+01	-1.30%	2.22E+02	2.33E+02	8.49E+02	8.30E+02	-1.83E+01	-2.15%
LAM	8.18E+02	6.84E+02	-1.34E+02	-16.39%	9.14E+01	5.96E+01	8.05E+02	6.87E+02	-1.18E+02	-14.68%
MES	5.16E+02	4.64E+02	-5.17E+01	-10.01%	1.32E+02	9.72E+01	4.76E+02	4.43E+02	-3.24E+01	-6.81%
MEX	4.77E+02	4.40E+02	-3.73E+01	-7.82%	7.44E+01	6.61E+01	4.90E+02	4.33E+02	-5.71E+01	-11.65%
ROW	5.50E+02	4.93E+02	-5.74E+01	-10.42%	1.43E+02	1.04E+02	5.13E+02	4.77E+02	-3.64E+01	-7.09%
USA	9.69E+02	9.83E+02	1.41E+01	1.46%	2.59E+02	2.71E+02	9.27E+02	9.43E+02	1.53E+01	1.65%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.51E+02	4.21E+02	-3.04E+01	-6.74%	5.94E+01	69.4398121	4.50E+02	4.22E+02	-2.72E+01	-6.04%
ANZ	1.00E-15	1.00E-15	0.00E+00	0.00%	3.75E-30	5.33E-23	1.00E-15	1.00E-15	0.00E+00	0.00%
ASI	7.41E+02	6.86E+02	-5.51E+01	-7.43%	1.07E+02	9.55E+01	7.21E+02	6.72E+02	-4.95E+01	-6.86%
CAN	1.66E+03	1.69E+03	3.16E+01	1.91%	1.04E+03	1.06E+03	1.09E+03	1.09E+03	4.65E+00	0.43%
CHN	9.06E+02	8.23E+02	-8.26E+01	-9.12%	1.60E+02	1.61E+02	8.51E+02	7.96E+02	-5.51E+01	-6.48%
EET	5.14E+02	5.04E+02	-1.01E+01	-1.96%	9.18E+01	9.34E+01	5.04E+02	4.92E+02	-1.26E+01	-2.50%
EUR	1.65E+03	1.68E+03	3.29E+01	2.00%	1.06E+03	1.08E+03	1.06E+03	1.08E+03	1.94E+01	1.83%
FSU	5.34E+02	5.26E+02	-8.39E+00	-1.57%	8.61E+01	8.74E+01	5.24E+02	5.17E+02	-7.39E+00	-1.41%
IDZ	8.22E+02	6.67E+02	-1.55E+02	-18.84%	1.07E+02	9.64E+01	8.16E+02	6.63E+02	-1.53E+02	-18.74%
IND	1.14E+03	1.04E+03	-1.07E+02	-9.34%	2.24E+02	2.00E+02	1.16E+03	1.05E+03	-1.11E+02	-9.55%
JPN	9.12E+02	9.21E+02	8.54E+00	0.94%	2.17E+02	2.21E+02	8.66E+02	8.69E+02	3.55E+00	0.41%
LAM	7.69E+02	7.06E+02	-6.34E+01	-8.25%	5.49E+01	5.51E+01	7.72E+02	7.06E+02	-6.62E+01	-8.57%
MES	5.05E+02	4.87E+02	-1.89E+01	-3.73%	7.85E+01	7.43E+01	4.82E+02	4.66E+02	-1.62E+01	-3.36%
MEX	5.16E+02	4.92E+02	-2.46E+01	-4.77%	4.99E+01	4.51E+01	5.22E+02	4.92E+02	-2.99E+01	-5.73%
ROW	5.45E+02	5.24E+02	-2.13E+01	-3.90%	8.49E+01	7.95E+01	5.24E+02	5.08E+02	-1.58E+01	-3.01%
USA	1.02E+03	1.04E+03	1.94E+01	1.90%	2.81E+02	2.83E+02	9.57E+02	9.77E+02	1.97E+01	2.05%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	4.65E-02	4.65E-02	-1.25E-05	-0.03%	3.49E-03	0.003463545	4.63E-02	4.64E-02	2.20E-05	0.05%
ANZ	1.20E-02	1.26E-02	5.43E-04	4.51%	1.64E-03	1.61E-03	1.19E-02	1.25E-02	5.39E-04	4.51%
ASI	5.45E-02	5.44E-02	-5.59E-05	-0.10%	4.37E-03	4.35E-03	5.41E-02	5.41E-02	5.40E-05	0.10%
CAN	5.71E-02	5.72E-02	7.50E-05	0.13%	9.08E-03	9.25E-03	6.04E-02	6.07E-02	2.45E-04	0.40%
CHN	6.10E-02	6.12E-02	1.96E-04	0.32%	7.43E-03	7.47E-03	6.33E-02	6.31E-02	-1.49E-04	-0.24%
EET	6.45E-02	6.45E-02	-7.77E-06	-0.01%	1.01E-02	1.01E-02	6.79E-02	6.78E-02	-1.49E-04	-0.22%
EUR	5.61E-02	5.61E-02	1.17E-06	0.00%	8.61E-03	8.67E-03	5.93E-02	5.93E-02	-3.65E-05	-0.06%
FSU	6.20E-02	6.20E-02	-1.32E-05	-0.02%	9.33E-03	9.39E-03	6.52E-02	6.50E-02	-1.90E-04	-0.29%
IDZ	4.71E-02	4.71E-02	3.75E-07	0.00%	5.50E-03	5.59E-03	4.56E-02	4.54E-02	-2.23E-04	-0.49%
IND	5.40E-02	5.41E-02	5.69E-05	0.11%	3.58E-03	3.64E-03	5.33E-02	5.36E-02	3.08E-04	0.58%
JPN	5.70E-02	5.71E-02	1.11E-04	0.20%	8.07E-03	8.04E-03	5.94E-02	5.90E-02	-4.36E-04	-0.73%
LAM	4.70E-02	4.70E-02	-4.43E-05	-0.09%	2.79E-03	2.78E-03	4.71E-02	4.71E-02	-1.85E-05	-0.04%
MES	6.27E-02	6.27E-02	3.26E-05	0.05%	7.26E-03	7.21E-03	6.43E-02	6.42E-02	-8.50E-06	-0.01%
MEX	5.31E-02	5.31E-02	9.50E-06	0.02%	3.94E-03	3.97E-03	5.27E-02	5.29E-02	1.67E-04	0.32%
ROW	6.56E-02	6.55E-02	-8.78E-05	-0.13%	8.75E-03	8.81E-03	6.81E-02	6.81E-02	-3.25E-05	-0.05%
USA	5.70E-02	5.70E-02	8.41E-05	0.15%	8.08E-03	8.10E-03	5.97E-02	5.93E-02	-3.69E-04	-0.62%

(8) Organic Carbon

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	3.26E+03	2.85E+03	-4.13E+02	-12.66%	5.73E+02	700.34421	3.26E+03	2.86E+03	-3.93E+02	-12.07%
ANZ	1.26E+04	1.00E-15	-1.26E+04	-100.00%	3.55E+03	0.00E+00	1.24E+04	1.00E-15	-1.24E+04	-100.00%
ASI	6.21E+03	5.26E+03	-9.46E+02	-15.24%	1.25E+03	9.11E+02	5.92E+03	5.13E+03	-7.89E+02	-13.31%
CAN	7.94E+03	5.49E+03	-2.45E+03	-30.83%	4.25E+03	3.19E+03	6.54E+03	3.86E+03	-2.68E+03	-41.02%
CHN	2.70E+03	2.33E+03	-3.72E+02	-13.75%	6.88E+02	5.81E+02	2.62E+03	2.24E+03	-3.76E+02	-14.38%
EET	3.65E+03	3.56E+03	-9.02E+01	-2.47%	8.99E+02	7.80E+02	3.53E+03	3.51E+03	-1.76E+01	-0.50%
EUR	7.54E+03	5.49E+03	-2.05E+03	-27.20%	3.94E+03	3.30E+03	6.24E+03	3.78E+03	-2.46E+03	-39.40%
FSU	3.86E+03	3.79E+03	-6.78E+01	-1.76%	8.40E+02	7.25E+02	3.75E+03	3.74E+03	-1.57E+01	-0.42%
IDZ	6.82E+03	5.01E+03	-1.81E+03	-26.55%	1.07E+03	8.15E+02	6.74E+03	4.96E+03	-1.78E+03	-26.36%
IND	3.30E+03	2.60E+03	-7.08E+02	-21.42%	7.48E+02	9.75E+02	3.19E+03	2.59E+03	-5.94E+02	-18.62%
JPN	5.65E+03	3.05E+03	-2.60E+03	-46.07%	1.54E+03	7.69E+02	5.48E+03	2.92E+03	-2.56E+03	-46.68%
LAM	6.53E+03	5.46E+03	-1.07E+03	-16.41%	7.54E+02	4.55E+02	6.41E+03	5.48E+03	-9.30E+02	-14.51%
MES	4.11E+03	3.69E+03	-4.15E+02	-10.11%	1.05E+03	7.72E+02	3.77E+03	3.50E+03	-2.66E+02	-7.07%
MEX	3.83E+03	3.53E+03	-2.97E+02	-7.76%	5.80E+02	5.04E+02	3.93E+03	3.48E+03	-4.49E+02	-11.41%
ROW	4.33E+03	3.88E+03	-4.52E+02	-10.44%	1.13E+03	8.18E+02	4.02E+03	3.74E+03	-2.79E+02	-6.93%
USA	6.07E+03	3.50E+03	-2.57E+03	-42.36%	1.70E+03	9.50E+02	5.87E+03	3.28E+03	-2.59E+03	-44.08%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	3.54E+03	3.30E+03	-2.37E+02	-6.71%	4.53E+02	531.9394	3.52E+03	3.31E+03	-2.06E+02	-5.86%
ANZ	1.10E+04	1.00E-15	-1.10E+04	-100.00%	2.77E+03	5.33E-23	1.10E+04	1.00E-15	-1.10E+04	-100.00%
ASI	5.91E+03	5.47E+03	-4.38E+02	-7.40%	8.64E+02	7.68E+02	5.75E+03	5.33E+03	-4.14E+02	-7.20%
CAN	7.66E+03	5.92E+03	-1.73E+03	-22.63%	4.55E+03	3.63E+03	5.82E+03	3.92E+03	-1.89E+03	-32.54%
CHN	2.94E+03	2.67E+03	-2.66E+02	-9.07%	5.20E+02	5.23E+02	2.76E+03	2.58E+03	-1.79E+02	-6.48%
EET	4.01E+03	3.93E+03	-7.85E+01	-1.96%	7.02E+02	7.14E+02	3.93E+03	3.84E+03	-8.95E+01	-2.28%
EUR	7.27E+03	5.92E+03	-1.34E+03	-18.47%	4.24E+03	3.71E+03	5.31E+03	3.90E+03	-1.41E+03	-26.54%
FSU	4.17E+03	4.11E+03	-6.67E+01	-1.60%	6.58E+02	6.68E+02	4.10E+03	4.04E+03	-6.47E+01	-1.58%
IDZ	6.49E+03	5.27E+03	-1.22E+03	-18.85%	8.42E+02	7.57E+02	6.44E+03	5.24E+03	-1.21E+03	-18.74%
IND	3.66E+03	3.32E+03	-3.40E+02	-9.28%	7.27E+02	6.47E+02	3.73E+03	3.37E+03	-3.53E+02	-9.48%
JPN	4.94E+03	3.21E+03	-1.73E+03	-35.05%	1.32E+03	7.61E+02	4.67E+03	3.01E+03	-1.66E+03	-35.47%
LAM	6.10E+03	5.59E+03	-5.02E+02	-8.24%	4.32E+02	4.26E+02	6.11E+03	5.59E+03	-5.17E+02	-8.47%
MES	4.00E+03	3.85E+03	-1.51E+02	-3.77%	6.27E+02	5.92E+02	3.81E+03	3.68E+03	-1.29E+02	-3.38%
MEX	4.12E+03	3.92E+03	-1.96E+02	-4.76%	3.84E+02	3.43E+02	4.17E+03	3.94E+03	-2.33E+02	-5.60%
ROW	4.27E+03	4.11E+03	-1.66E+02	-3.90%	6.72E+02	6.28E+02	4.10E+03	3.97E+03	-1.22E+02	-2.98%
USA	5.43E+03	3.65E+03	-1.77E+03	-32.69%	1.65E+03	1.02E+03	4.94E+03	3.44E+03	-1.50E+03	-30.33%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	3.78E+03	3.64E+03	-1.42E+02	-3.76%	3.84E+02	401.84336	3.77E+03	3.59E+03	-1.86E+02	-4.93%
ANZ	1.01E+04	1.00E-15	-1.01E+04	-100.00%	2.36E+03	7.38E-23	1.02E+04	1.00E-15	-1.02E+04	-100.00%
ASI	6.02E+03	5.73E+03	-2.88E+02	-4.77%	7.15E+02	6.44E+02	5.85E+03	5.54E+03	-3.06E+02	-5.23%
CAN	7.54E+03	6.25E+03	-1.29E+03	-17.07%	4.69E+03	3.94E+03	5.63E+03	4.28E+03	-1.35E+03	-24.04%
CHN	3.05E+03	2.90E+03	-1.52E+02	-4.96%	4.67E+02	4.56E+02	2.87E+03	2.73E+03	-1.39E+02	-4.86%
EET	4.36E+03	4.29E+03	-6.50E+01	-1.49%	6.78E+02	6.79E+02	4.30E+03	4.20E+03	-1.04E+02	-2.43%
EUR	7.14E+03	6.18E+03	-9.60E+02	-13.44%	4.38E+03	3.93E+03	5.21E+03	4.23E+03	-9.82E+02	-18.85%
FSU	4.46E+03	4.41E+03	-5.20E+01	-1.17%	6.44E+02	6.44E+02	4.49E+03	4.35E+03	-1.35E+02	-3.01%
IDZ	6.71E+03	5.56E+03	-1.15E+03	-17.20%	8.61E+02	7.84E+02	6.65E+03	5.49E+03	-1.16E+03	-17.44%
IND	3.67E+03	3.48E+03	-1.86E+02	-5.08%	7.37E+02	6.38E+02	3.77E+03	3.50E+03	-2.66E+02	-7.06%
JPN	4.72E+03	3.44E+03	-1.28E+03	-27.11%	1.37E+03	8.61E+02	4.46E+03	3.29E+03	-1.17E+03	-26.19%
LAM	6.07E+03	5.74E+03	-3.37E+02	-5.55%	4.10E+02	3.79E+02	6.08E+03	5.75E+03	-3.37E+02	-5.53%
MES	4.05E+03	3.93E+03	-1.17E+02	-2.89%	4.94E+02	4.73E+02	3.91E+03	3.80E+03	-1.07E+02	-2.73%
MEX	4.39E+03	4.21E+03	-1.75E+02	-3.98%	2.50E+02	2.14E+02	4.41E+03	4.22E+03	-1.86E+02	-4.23%
ROW	4.38E+03	4.28E+03	-1.02E+02	-2.33%	5.19E+02	4.98E+02	4.25E+03	4.13E+03	-1.19E+02	-2.81%
USA	5.19E+03	3.88E+03	-1.31E+03	-25.20%	1.70E+03	1.15E+03	4.59E+03	3.54E+03	-1.05E+03	-22.86%

(9) Nitrate Aerosols

	2001-2100									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.27E+02	1.13E+02	-1.42E+01	-11.16%	37.937153	33.222012	1.19E+02	1.05E+02	-1.41E+01	-11.80%
ANZ	1.92E+04	1.92E+04	-3.06E+01	-0.16%	4958.6994	5.04E+03	1.89E+04	1.89E+04	9.50E+00	0.05%
ASI	1.43E+02	1.39E+02	-4.28E+00	-2.99%	20.118141	1.69E+01	1.44E+02	1.40E+02	-4.62E+00	-3.20%
CAN	5.39E+00	6.52E+00	1.13E+00	20.90%	6.4007861	7.16E+00	3.01E+00	3.98E+00	9.67E-01	32.14%
CHN	1.24E+02	1.04E+02	-2.00E+01	-16.19%	61.908524	4.10E+01	9.95E+01	8.98E+01	-9.73E+00	-9.78%
EET	7.12E+01	8.01E+01	8.88E+00	12.47%	77.77706	7.87E+01	4.66E+01	5.70E+01	1.04E+01	22.24%
EUR	1.63E+01	1.59E+01	-4.46E-01	-2.74%	32.723644	3.09E+01	2.68E+00	3.17E+00	4.94E-01	18.44%
FSU	1.03E+02	1.16E+02	1.27E+01	12.30%	83.308934	8.47E+01	7.74E+01	8.90E+01	1.17E+01	15.10%
IDZ	1.30E+02	1.10E+02	-1.97E+01	-15.20%	32.612973	3.25E+01	1.27E+02	1.07E+02	-2.00E+01	-15.73%
IND	2.03E+02	1.73E+02	-3.02E+01	-14.86%	131.39416	1.12E+02	1.83E+02	1.53E+02	-2.99E+01	-16.32%
JPN	1.44E+02	1.33E+02	-1.11E+01	-7.67%	240.28931	2.26E+02	1.29E+01	1.14E+01	-1.47E+00	-11.44%
LAM	2.12E+02	1.97E+02	-1.56E+01	-7.37%	24.667745	2.11E+01	2.09E+02	1.95E+02	-1.44E+01	-6.90%
MES	1.02E+02	9.29E+01	-8.73E+00	-8.59%	28.078094	2.51E+01	1.01E+02	9.23E+01	-8.77E+00	-8.68%
MEX	1.84E+02	1.67E+02	-1.63E+01	-8.89%	37.17824	2.63E+01	1.78E+02	1.67E+02	-1.07E+01	-6.01%
ROW	8.38E+01	7.44E+01	-9.46E+00	-11.29%	30.527107	2.64E+01	7.78E+01	7.02E+01	-7.58E+00	-9.74%
USA	1.92E+02	1.77E+02	-1.52E+01	-7.91%	237.84625	2.20E+02	8.21E+01	7.72E+01	-4.89E+00	-5.96%

	2001-2050									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.16E+02	1.11E+02	-5.23E+00	-4.51%	35.120044	32.89237	1.08E+02	1.04E+02	-4.37E+00	-4.04%
ANZ	1.55E+04	1.54E+04	-7.39E+01	-0.48%	2918.321	3.09E+03	1.54E+04	1.53E+04	-9.45E+01	-0.61%
ASI	1.49E+02	1.43E+02	-6.63E+00	-4.44%	18.934943	1.77E+01	1.52E+02	1.44E+02	-7.57E+00	-4.98%
CAN	9.42E-01	1.01E+00	6.68E-02	7.10%	1.1687671	1.38E+00	4.46E-01	4.26E-01	-2.04E-02	-4.58%
CHN	9.15E+01	8.82E+01	-3.29E+00	-3.60%	29.521291	2.71E+01	8.58E+01	8.43E+01	-1.48E+00	-1.73%
EET	1.05E+02	1.08E+02	2.59E+00	2.46%	94.852219	9.69E+01	6.73E+01	6.68E+01	-5.37E-01	-0.80%
EUR	6.86E-01	6.82E-01	-4.17E-03	-0.61%	0.9352347	1.06E+00	1.94E-01	1.16E-01	-7.84E-02	-40.38%
FSU	1.38E+02	1.40E+02	1.58E+00	1.14%	101.57647	1.04E+02	9.48E+01	9.26E+01	-2.22E+00	-2.34%
IDZ	1.34E+02	1.21E+02	-1.23E+01	-9.20%	33.224644	3.33E+01	1.30E+02	1.19E+02	-1.18E+01	-9.03%
IND	1.08E+02	1.02E+02	-5.83E+00	-5.39%	7.75E+01	7.21E+01	8.90E+01	8.45E+01	-4.41E+00	-4.95%
JPN	4.93E+00	4.74E+00	-1.92E-01	-3.89%	5.7953083	5.71E+00	2.13E+00	2.32E+00	1.92E-01	9.02%
LAM	2.03E+02	1.96E+02	-7.67E+00	-3.77%	20.143683	1.85E+01	2.00E+02	1.93E+02	-7.29E+00	-3.64%
MES	1.04E+02	9.99E+01	-4.25E+00	-4.09%	22.436461	2.08E+01	1.01E+02	9.68E+01	-4.01E+00	-3.97%
MEX	1.75E+02	1.63E+02	-1.16E+01	-6.66%	29.503034	2.32E+01	1.72E+02	1.63E+02	-9.09E+00	-5.28%
ROW	8.59E+01	8.44E+01	-1.53E+00	-1.78%	25.132255	2.40E+01	8.17E+01	8.06E+01	-1.18E+00	-1.44%
USA	2.48E+01	2.32E+01	-1.55E+00	-6.28%	24.151525	2.29E+01	1.54E+01	1.43E+01	-1.12E+00	-7.27%

	2001-2020									
	mean				standard deviation		median			
	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a	no policy (a)	450ppm (b) policy	no policy (a)	450ppm (b) policy	b-a	%change (b-a)/a
AFR	1.08E+02	1.05E+02	-2.50E+00	-2.31%	34.534541	33.187122	1.01E+02	9.79E+01	-2.95E+00	-2.93%
ANZ	1.33E+04	1.31E+04	-2.32E+02	-1.75%	2150.1058	2.27E+03	1.32E+04	1.28E+04	-3.83E+02	-2.89%
ASI	1.45E+02	1.42E+02	-3.70E+00	-2.55%	19.304169	1.96E+01	1.47E+02	1.42E+02	-5.15E+00	-3.50%
CAN	3.39E-01	1.74E-01	-1.65E-01	-48.56%	0.4920567	1.61E-01	2.09E-01	1.28E-01	-8.13E-02	-38.84%
CHN	7.25E+01	7.09E+01	-1.51E+00	-2.08%	15.956716	1.61E+01	7.09E+01	6.99E+01	-9.78E-01	-1.38%
EET	1.24E+02	1.22E+02	-1.72E+00	-1.38%	114.98759	1.14E+02	6.34E+01	6.48E+01	1.46E+00	2.30%
EUR	5.65E-01	3.83E-01	-1.82E-01	-32.22%	0.8544715	8.32E-01	8.77E-02	9.19E-03	-7.85E-02	-89.52%
FSU	1.54E+02	1.52E+02	-2.28E+00	-1.48%	121.87938	1.21E+02	9.30E+01	8.99E+01	-3.11E+00	-3.34%
IDZ	1.41E+02	1.27E+02	-1.43E+01	-10.09%	34.815584	3.58E+01	1.37E+02	1.24E+02	-1.22E+01	-8.93%
IND	5.88E+01	5.81E+01	-6.35E-01	-1.08%	34.806213	3.52E+01	4.94E+01	4.83E+01	-1.16E+00	-2.34%
JPN	1.68E+00	1.65E+00	-2.68E-02	-1.60%	2.7936623	2.64E+00	5.44E-01	5.87E-01	4.29E-02	7.89%
LAM	1.97E+02	1.95E+02	-2.74E+00	-1.39%	19.259538	1.82E+01	1.95E+02	1.91E+02	-3.64E+00	-1.87%
MES	9.54E+01	9.26E+01	-2.79E+00	-2.93%	18.558978	1.83E+01	9.29E+01	9.10E+01	-1.93E+00	-2.08%
MEX	1.55E+02	1.48E+02	-6.96E+00	-4.48%	22.236865	1.96E+01	1.54E+02	1.49E+02	-4.48E+00	-2.91%
ROW	8.60E+01	8.51E+01	-8.63E-01	-1.00%	24.225247	2.41E+01	8.45E+01	8.32E+01	-1.31E+00	-1.55%
USA	6.23E+00	5.81E+00	-4.19E-01	-6.72%	4.3075212	3.88E+00	4.14E+00	3.98E+00	-1.52E-01	-3.68%

Bibliography

A.P. Sokolov, C. S. (2005). *The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation.* Cambridge, MA, USA: MIT Joint Program on the Science and Policy of Global Climate, Report No. 124 .

AEA. (n.d.). *UK Air Quality Archive* . Retrieved July 30th, 2010, from http://www.airquality.co.uk/what_are_we_doing.php

B. Metz, O. D. (2007). *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007* . Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press .

B. Metz, O. D. (2001). *Contribution to the Third Assessment Report of the International Panel on Climate Change, 2001: Mitigation.* Cambridge and New York: Cambridge University Press.

Carmichael, V. R. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience Vol1* .

Cohen, J., & Prinn, R. (2009). *Development of a Fast and Detailed Model of Urban-Scale Chemical and Physical Processing.* Cambridge, MA, USA: MIT Joint Program on the Science and Policy of Global Climate, Report No. 181.

DH, E. (1999). Gas phase chemistry of the troposphere. In Global Aspects of Atmospheric Chemistry. In R. Zellner, *Topics in Physical Chemistry 6* (pp. 21-109). Germany: Springer-Verlag-Darmstädt-Steinkopff.

Ekins, P. (1996). The secondary benefits of CO2 abatement: How much emission reduction do they justify? *Ecol. Econ. 16* , 13-24.

ENVIRON. (2010, March). *CAMx User's Guide, Comprehensive Air Quality Model with Extensions* . Retrieved July 30th , 2010, from http://www.camx.com/files/CAMxUsersGuide_v5.20.pdf

European Environment Agency. (2003). *Europe's Environment: The Third Assessment, Environmental assessment report No 10.* Copenhagen: EEA.

G F Nemet, T. H. (2010). Implications of incorporating air-quality co-benefits into climate change policymaking. *Environ. Res. Lett. 5* , 014007.

Hansen, J. E. (1990). Sun and dust versus greenhouse gases: an assessment of their relative roles in global cilamte change. *Nature* , vol(346), Review Article.

Houghton, J. T. (2001). *Contribution of Working Group I to the Third Assessment Report on*

Climate Change 2001: The Scientific Basis. Cambridge and New York: Cambridge University Press.

Hubbs, P. V. (2000). *Introduction to Atmospheric Chemistry.* Cambridge: Cambridge University Press.

IEA. (2009). *CO2 Emissions from Fuel Combustion Highlight (2009 Edition).* Paris, France: International Energy Agency.

IPCC. (1995). *Climate Change 1995: IPCC Second Assessment Report.* Cambridge and New York: Cambridge University Press.

Jacobson, M. Z. (2002). Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107* , NO. D19, 4410.

James Hansen, M. S. (2000). Global warming in the twenty-first century: An alternative scenario. *Proc. Natl. Acad. Sci. 97* , 9875-9880.

James J. McCarthy, O. F. (2001). *Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change 2001: Impacts, Adaptation, and Volunerability.* Cambridge and New York: Cambridge University Press.

John H. Seinfeld, S. N. (2006). *Atmospheric Chemistry and Physics From Air Pollution to Climate Change, Second Edition.* Wiley Interscience.

Kupiainen, K. a. (2007). *Primary emissions of submicron and carbonaceous particles in Europe and the potential for their control.* Laxenburg: International Institute for Applied Systems Analysis.

Kuylenstierna, J., Mills, R., & Hicks, K. (2010, March). *Progress in Developing a Framework for Integrated Co-benefits Strategies in the Global Atmospheric Pollution Forum.* Retrieved July 30th, 2010, from http://www.iges.or.jp/jp/cp/pdf/activity20100311cb/12_0850Forum.pdf

Levy, H. I. (1972). Photochemistry of the lower troposphere . *Planetary and Space Science* , 919-935.

Monika Mayer, C. W. (2000). *Linking Local Air Pollution to Global Chemistry and Climate.* MT Joint Program on the Science and Policy of Global Climate, Report No. 63.

Morgenstern, R. (2000). Baseline issues in the estimation of the ancillary benefits of greenhouse gas mitigation policies. In OECD, *Ancillary Benefits and Costs of Greenhouse Gas Mitigation* (pp. 95-122). Paris, France: OECD publications .

Mort Webster, M. A. (1996). *Application of Probabilistic Collocation Method for Uncertainty Analysis of a Simple Ocean Model.* Cambridge, MA, USA: MIT Joint Program on the Science and Policy of Global Climate, Report No.4.

Nishikawa, J. (2008, March 26th). *Co-benefits Approach and Emission Trading.* Retrieved July 30th , 2010, from http://www.kyomecha.org/pdf/080326pm_nishikawa.pdf

Organisation for Economic Co-operation and Development. (2000). Ancillary Benefits and Costs of Greenhouse Gas Mitigation. *Proceedings of an IPCC Co-Sponsored Workshop held on 27-29 March 2000.* Paris, France: OECD Publications .

Pearce, D. (2000). *POLICY FRAMEWORKS FOR THE ANCILLARY BENEFITS OF CLIMATE CHANGE POLICIES, CSERGE Working Paper GEC 2000-11.*

Pittel, K., & Rübbelke, D. T. (2008). Climate policy and ancillary benefits: A survey and integration into the modeling of international negotiations on climate change. *Ecological Economics 68* , 210-220.

Raes, F. (2006, March). *Climate Change and Air Pollution - Research and Policy.* Retrieved July 30th, 2010, from Global Change NewsLetter No. 65: http://www.igbp.net/documents/NL_65_7.pdf

Rob Swart, M. A. (2004). A GOOD CLIMATE FOR CLEAN AIR: LINKAGE BETWEEN CLIMATE CHANGE AND AIS POLLUTION. *Climate Change 66* , 263-269.

Ronald G. Prinn, J. R. (2005). *Effects of Air Pollution Control on Climate.* Cambridge, MA, USA: MIT Joint Program on the Science and Policy of Global Climate, Report No. 118 .

Sarofim, M. C. (2007). *Climate Policy Design: Interactions among Carbon Dioxide, Methane, and Urban Air Pollution Constraints, PhD dissertation.*

Sebastien Dessus, D. O. (2003). Climate Policy without Tears: CGE-Based Ancillary Benefits Estimates for Chile. *Environ. Res. Econ. 25* , 287-317.

Sergey Paltsev, J. M. (2005). *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4.* Cambridge, MA, USA: MIT Joint Program on the Science and Policy of Global Change.

Sokolov, A. P. (2009). Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *J. Climate* , doi: 10.1175/2009JCLI2863.1.

Tatang, M. A. (1997). An efficient method for parametric uncertainty analysis of numerical geophysical models. *Journal of Geophysical Research-Atmospheres 102(D18)* ,

21925-21932.

UNFPA. (2007). *State of World Population 2007 – Unleashing the Potential of Urban Growth.* New York, USA: United Nations Population Fund.

United Nations. (2005). *Level of Urbanization (2003) and Annual Urban Growth Rate (Average for 2000-2005).* United Nations Department of Economic and Social Affairs, Population Division.

US.EPA. (2010, June 24th). *Clean Air Act* . Retrieved July 30th , 2010, from US. EPA: http://www.epa.gov/air/caa/

USEPA. (2010). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008.* U.S. Environmental Protection Agency.

Wang, W. D. (1986). Trace gases and other potential perturbations to globa climate. *Rev. Geophysics.24(1)* , 110-140.

Webster, M. A. (2010). Analysis of climate policy targets under uncertainty. *Climatic Change* , (submitted).

WUP. (2009). *World Urbanization Prospects, the 2009 Revision.* New York, USA: United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section.

Xuehua Zhou, J. G. (2009). Measurement of black carbon aerosols near two Chinese megacities and the implications for improving emission inventories. *Atmospheric Environment. Volume 43, Issue 25* , 3918-3924 .